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Advancing Integrated Fish Farming in Nigeria: Climate-Smart Innovations and Policy Strategies

AGBEJA, Y.E.* and UMMA, S.B

Department of Aquaculture and Fisheries Management, University of Ibadan, Ibadan, Nigeria
Corresponding author: eniolagbeja@yahoo.com

Abstract

Nigeria faces a significant gap between fish demand and domestic supply, with imports covering nearly half of consumption. Integrated fish farming offers a pathway to expand production while addressing resource and environmental challenges. This study applies an evidence-based policy analysis of scholarly, institutional, and grey literature published up to 2022. Using the Climate-Smart Aquaculture (CSAq) framework, supported by institutional and diffusion of innovation theories, it assesses both the benefits of emerging technologies and the conditions influencing their adoption. Results show that solar-powered aeration, biofloc systems, and aquaponics can lower costs, improve resilience to climate variability, and reduce environmental impacts. Yet uptake is constrained by limited finance, weak extension support, and inadequate regulatory incentives. The study concludes that targeted reforms in credit access, extension training, and sustainability-focused regulations are essential to scale these innovations. Strengthening such enablers would reduce Nigeria's fish deficit, enhance food security, and align aquaculture with climate adaptation priorities.

Keywords: Climate-Smart, Integrated, Sustainable, Innovation, Policy

INTRODUCTION

Fish is a cornerstone of food security in Nigeria, providing approximately 40% of the country's animal protein intake. Yet, domestic fish supply falls significantly short of national demand. Annual fish consumption is estimated at 3.6 million metric tons, while local production remains around 1.1–1.2 million tons, leaving a deficit that is met through costly imports (Subasinghe et al., 2021). Nigeria spends about USD 1 billion annually on fish imports, which constitute roughly 45% of total fish supply (Odioko and Becer, 2022). Bridging this supply gap through sustainable aquaculture expansion has become a national priority, as reflected in government strategies to develop aquaculture as a key food value chain in order to reduce imports and conserve foreign exchange (Seafood Source, 2021). Aquaculture in Nigeria has grown rapidly in recent decades, averaging 13.6% annual growth in the early 2000s (FAO, 2020), making the country Africa's second-largest aquaculture producer (Kaleem and Bio Singou Sabi, 2021). However, growth has plateaued in recent years, constrained by challenges such as rising input costs, inadequate infrastructure, and environmental stresses (FAO, 2020). Against this backdrop, integrated fish farming is increasingly viewed as a promising strategy for enhancing both productivity and sustainability. Broadly defined, integrated fish farming links aquaculture with other farming or resource systems so that wastes and outputs from one component serve as inputs for another (Bolorunduro et al., 2013). Classical examples include fish-livestock systems (e.g., fertilizing fish ponds with poultry manure) and fish-crop systems (e.g., rice-fish farming). By recycling nutrients and sharing resources, integration can improve resource-use efficiency, lower costs, and diversify farm outputs. In Nigeria, integrated aquaculture-agriculture practices have been documented in many states. One survey reported that about half of fish farmers combine aquaculture with poultry, piggery, or other livestock enterprises, while integrated fish-crop farming is also on the rise. These systems align with circular economy principles by turning waste into inputs (Zira et al., 2015; Ajani et al., 2020), and they dovetail with Nigeria's traditional mixed-farming practices, potentially easing adoption. Nonetheless, integrated aquaculture remains largely small-scale. Wider uptake has been hampered by knowledge gaps, limited access to capital, and insufficient policy support; particularly as extension services have historically focused on monoculture systems (WorldFish, 2022a).

Climate change further adds urgency to transforming Nigeria's aquaculture sector. Rising temperatures, erratic rainfall, and extreme weather events threaten fish farming through heightened risks of disease outbreaks, water stress, and pond flooding. Nigeria is among the ten countries most vulnerable to climate change impacts on fisheries and aquaculture (Okon et al., 2021). Building climate resilience in aquaculture is therefore critical for sustaining production. The concept of climate-smart aquaculture (CSAQ) provides a useful framework. CSAQ is defined as aquaculture that "sustainably increases productivity, enhances resilience (adaptation), reduces or removes greenhouse gas emissions (mitigation), and advances national food security and development goals" (UNDP, 2022). This mirrors the climate-smart agriculture paradigm, which emphasizes a "triple win" of increased output, adaptation, and mitigation (FAO, 2013). Integrated fish farming, when coupled with appropriate technologies, can serve as a vehicle for CSAQ. Such systems typically reuse water (increasing drought resilience), recycle nutrients (reducing pollution and emissions), and boost yields from the same land and water footprint.

This study therefore aims to review and critically evaluate technological innovations that can advance CSAQ in Nigeria, with a focus on integrated fish farming systems. Specifically, it assesses the current status and challenges of integrated aquaculture-agriculture practices at the national level; analyzes emerging technological and management approaches; such as renewable energy applications, digital tools and sensors, automated water-quality monitoring, biofloc systems, aquaponics, and recirculating aquaculture systems (RAS), with a view to evaluate their contributions to the three pillars of CSAQ (sustainable productivity, climate adaptation, and mitigation of greenhouse gas emissions); and examines Nigeria's institutional and policy frameworks to identify barriers and enablers for scaling these innovations. By synthesizing scientific literature and field experiences, the paper provides an academic foundation for policymakers to design strategies that align aquaculture growth with Nigeria's food security, low-carbon development, and environmental sustainability goals. The insights are intended to inform forthcoming fisheries and aquaculture policy frameworks (e.g., the National Fisheries and Aquaculture Policy) and contribute to the implementation of national climate adaptation and resilience plans.

Conceptual Framework

This study employs an integrative conceptual framework that combines the Climate-Smart Aquaculture (CSAQ) approach with Institutional Theory and Diffusion of Innovation (DOI) theory to analyze adoption dynamics in Nigeria's aquaculture sector.

i. Climate-Smart Aquaculture (CSAQ) Framework

The CSAQ framework, adapted from FAO's climate-smart agriculture paradigm, emphasizes three interrelated goals: improving productivity (e.g., achieving higher yields through efficient input use), strengthening resilience (e.g., sustaining production under climate variability and water stress), and reducing environmental impacts (e.g., lowering waste, emissions, and ecological footprints) (UNDP, 2022; FAO, 2013). It provides the technical foundation for assessing whether aquaculture practices can achieve sustainable production gains while mitigating climate risks. Building on this technical lens, Institutional Theory highlights the structural changes required to create enabling conditions for adoption.

ii. Institutional Theory

Institutional Theory explains how socio-political and economic structures shape the uptake of innovations. Institutions are expressed through regulative (laws and policies), normative (standards, networks, and professional roles), and cognitive (shared perceptions and legitimacy) dimensions (Scott, 2005). These determine how easily farmers can access, trust, and integrate new practices. Institutional Theory also highlights the types of change needed for scaling aquaculture at national level: regulative reforms (e.g., supportive credit schemes, clear environmental safeguards), normative strengthening (e.g., professional extension services, certification standards), and cognitive shifts (e.g., awareness-building, demonstration programs). While institutions shape the enabling environment, adoption at the farm level is further influenced by how farmers perceive the innovations themselves—an area clarified by Diffusion of Innovation theory.

iii. Diffusion of Innovation (DOI) Theory

DOI theory focuses on why adoption varies among individuals by emphasizing five perceived attributes of innovations (Rogers, 2003). These include: relative advantage (the perceived economic or performance benefits over current practices), compatibility (fit with existing systems and cultural norms), complexity (the degree of difficulty in understanding and using the practice), trialability (opportunities to test on a small scale before full adoption), and observability (the visibility of results to others). In aquaculture, these perceptions strongly influence whether innovations spread beyond a few pioneers. When combined with CSAQ and Institutional Theory, DOI provides a behavioral dimension, explaining how farmer perceptions interact with institutional settings to determine adoption outcomes.

By integrating CSAQ, Institutional Theory, and DOI, this study captures three critical dimensions of adoption: (i) the technical and environmental benefits of climate-smart practices, (ii) the institutional reforms needed to create enabling environments, and (iii) the farmer-level dynamics shaped by perceptions of new technologies. This comprehensive approach underscores that successful scaling of climate-smart aquaculture in Nigeria requires not only innovative practices but also supportive institutions and favorable farmer perceptions working in tandem. As illustrated in Figure 1, these three perspectives interact to provide a holistic framework for understanding and guiding adoption pathways.

METHODOLOGY

Study area

This research is structured as an evidence-based policy analysis, employing a qualitative literature review to synthesize knowledge on integrated aquaculture, technological innovations, and fisheries policy in Nigeria. The method draws on both peer-reviewed and grey literature to capture academic insights as well as practice-oriented evidence.

i. Data Sources Key information was obtained from peer-reviewed journal articles, academic reviews, and conference proceedings, complemented by policy documents, institutional reports, NGO publications, and development partner briefs. Publications up to 2022 were included to ensure coverage of both foundational research and the most recent trends. The review focused on materials addressing aquaculture in Nigeria, while also drawing on relevant global studies to provide comparative insights. Searches were conducted using databases such as Google Scholar, Scopus, FAO repositories, and institutional libraries, supplemented with grey literature from national agencies, NGOs, and international development partners.

ii. Innovation Selection The selection of technological innovations was guided by three criteria. First, each innovation directly addresses critical constraints in Nigerian aquaculture, including high feed costs, unreliable energy, water quality fluctuations, and limited land and water availability. Second, the innovations align with the three pillars of Climate-Smart Aquaculture (CSAQ): productivity, resilience, and mitigation, making them relevant to Nigeria's food security and sustainability priorities. Third, the choices were informed by evidence from both global and Nigerian contexts, ensuring that selected technologies had demonstrated feasibility and growing recognition among policymakers, entrepreneurs, and research institutions. Based on these considerations, six innovations were prioritized: solar-powered aeration, mobile farm management tools, IoT water-quality sensors, biofloc technology, aquaponics, and recirculating aquaculture systems (RAS).

iii. Contribution Statement: This study advances the literature on Climate-Smart Aquaculture (CSAq) in Nigeria by integrating institutional and diffusion of innovation perspectives to show not only the technical potential of CSAq technologies but also the institutional reforms and adoption dynamics required to achieve their large-scale uptake.

iv. Limitations A limitation of this approach is the scarcity of peer-reviewed studies on climate-smart aquaculture in Nigeria, which necessitated reliance on grey literature such as policy briefs and institutional reports. While these sources provide up-to-date, context-specific evidence, they may lack the methodological rigor of peer-reviewed research. To address this, findings were triangulated across multiple sources wherever possible. This limitation underscores the need for more empirical studies on climate-smart aquaculture adoption in Nigeria.

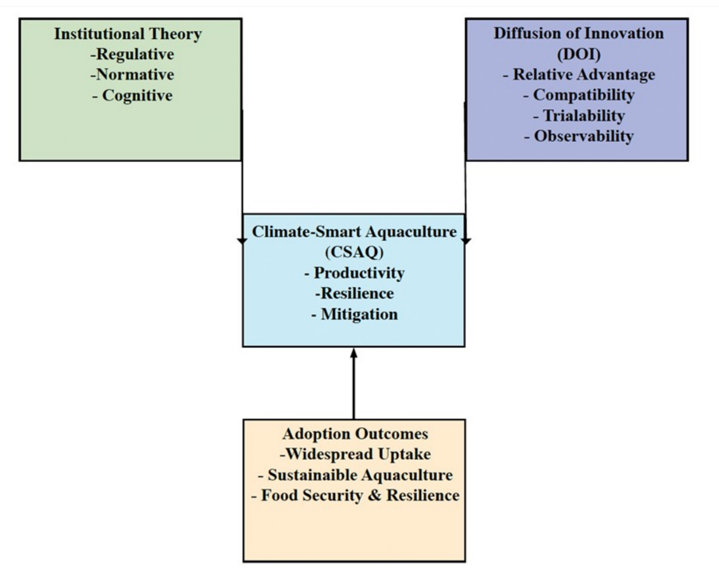

Figure 1: Integrative Conceptual Framework for Climate-Smart Aquaculture Adoption in Nigeria

Current State of Integrated Fish Farming in Nigeria

Nigeria's aquaculture sector remains dominated by freshwater pond culture, particularly of African catfish (Clarias gariepinus and its hybrids) and tilapia, produced largely in monoculture systems (FAO, 2020; WorldFish, 2022a). According to FAO estimates, over 80% of aquaculture production in Nigeria is from monoculture, with integrated fish farming accounting for less than 15% of systems in practice (FAO, 2020). Integrated aquaculture, where fish production is combined with crops, livestock, or other aquatic species, remains at a relatively early stage, though its role is gaining recognition in policy and research discourse.

i. Traditional Integration Practices In rural areas, traditional forms of integration are more common. Farmers often construct poultry or pigsties adjacent to ponds, applying manure directly as fertilizer to stimulate natural feed production (Bolorunduro et al., 2013; Zira et al., 2015). These systems improve nutrient recycling, reduce input costs, and diversify household food supply. For example, Zira et al. (2016) observed that fish–livestock integration increased household food security and generated supplementary income, contributing to poverty reduction. Similarly, integrated rice–fish culture has been piloted in states such as Ebonyi and Kebbi. Farmers reported yield increases of 10–15% in rice alongside additional fish harvests (Onoh et al., 2020). Despite these benefits, uptake remains limited due to land tenure issues, cultural barriers (e.g., avoidance of pig–fish integration in predominantly Muslim northern states), and inadequate technical knowledge for managing multi-component systems (Ajani et al., 2020; WorldFish, 2022b).

ii. Emerging and Technology-Driven Systems

In peri-urban contexts, there is growing interest in more technologically advanced integrated systems. Entrepreneurs in Lagos, Abuja, and Port Harcourt have piloted aquaponics; integrating recirculating fish tanks with hydroponic vegetable beds to serve niche urban markets demanding fresh, high-quality produce. The Sustainable Aquaponics for Nutritional and Food Security (SANFU) pilot in Lagos demonstrated that compact aquaponics units could generate 20–30 kg of fish and 100–120 kg of vegetables per cycle in small spaces, significantly contributing to urban nutrition security (Obirikorang et al., 2021). Farmers and investors, however, identify high startup costs (ranging from ₦1.5–2.5 million per unit), lack of technical expertise, and limited market awareness as major barriers to wider adoption. Integrated multi-trophic aquaculture (IMTA); a system which co-cultures species such as finfish, shellfish, and seaweed for nutrient recycling; remains virtually absent in Nigeria at the time of this study. The absence reflects both ecological and institutional constraints such as Nigeria's aquaculture is heavily inland and freshwater-based, while IMTA models are more commonly developed in coastal or marine settings. Furthermore, there is limited RD capacity, weak regulatory frameworks for multi-species farming, and no established value chains for shellfish or seaweed production. Nonetheless, IMTA is increasingly recognized in research and policy discussions as a potential climate-smart innovation with future relevance for Nigeria's coastal aquaculture (WorldFish, 2022a).

iii. Stakeholder Perspectives and Institutional Roles

Surveys of smallholder farmers suggest cautious interest in integration, with many acknowledging benefits such as reduced input costs and diversified income but expressing concerns over technical complexity, labor intensity, and market access for secondary outputs (Ajani et al., 2020). Institutional support has been modest: while universities and research institutes (e.g., NIFFR, University of Ibadan) have piloted rice–fish–poultry systems and aquaponics, scaling remains limited due to weak extension services and lack of financial incentives. Market dynamics also play a role; urban demand for premium fish and vegetables is growing, but rural markets remain dominated by low-cost catfish, limiting profitability incentives for smallholders to transition into more complex integrated systems.

iv. Comparative Overview

Table 1 contrasts traditional and emerging integrated systems in Nigeria at the time of this study, highlighting adoption levels, productivity, costs, and climate-smart potential. Integrated fish farming in Nigeria is at a promising stage. Conventional systems such as fish–livestock and rice–fish culture remain underutilized, yet they provide a foundation for resource efficiency and household resilience. Emerging systems like aquaponics and IMTA point toward innovative, climate-smart pathways, particularly for urban and coastal contexts. However, expansion is constrained by land and cultural barriers, technical gaps, high capital costs, and absent policy incentives. With targeted support from institutions, markets, and policymakers, integrated aquaculture could play a central role in enhancing Nigeria's food security, climate resilience, and sustainable development trajectory.

Table 1: Comparative Overview: Traditional and Emerging Integrated Systems in Nigeria

System	Adoption Level	Productivity / Yield	Cost Profile	Climate-Smart Benefits	Constraints
Fish–Livestock (e.g., poultry, pigs)	Moderate in rural areas (<10% of farms)	Enhances pond fertilization; modest fish yield gains (10–15%)	Low input costs; manure readily available	Nutrient recycling, diversified income	Cultural barriers; disease risks; weak technical knowledge
Rice–Fish Culture	Pilots in Ebonyi, Kebbi (<5% adoption)	10–15% higher rice yields + fish harvest	Low–medium cost (requires land modification)	Improved food security, water use efficiency	Land tenure issues; low farmer awareness
Aquaponics (fish–vegetables)	Early stage (<1% adoption, peri-urban)	20–30 kg fish + 100–120 kg vegetables per cycle	High upfront costs (₦1.5–2.5m)	Efficient water use, urban food security, premium markets	Capital intensive; technical expertise required
Integrated Multi-Trophic Aquaculture (IMTA)	Absent in Nigeria	Untested locally	High R&D and setup costs	High nutrient recycling, aligns with Blue Economy	Ecological constraints; weak regulatory and market support

Technological Innovations for Climate-Smart

Modern innovations are emerging to tackle persistent challenges in Nigerian aquaculture such as unreliable energy, inefficient feed use, poor water quality, and resource waste, all with climate and sustainability implications. This study applies the Climate-Smart Aquaculture (CSAQ) framework, which evaluates innovations through three dimensions: productivity gains, resilience/adaptive capacity, and mitigation of environmental impacts. Six innovations are highlighted, namely, solar-powered aeration, mobile farm management tools, IoT-based water quality monitoring, biofloc technology, aquaponics, and recirculating aquaculture systems (RAS). Each is assessed in terms of how it improves efficiency and yields (productivity), strengthens the capacity of farms to withstand climate variability and operational risks (resilience), and reduces greenhouse gas emissions and ecological footprints (mitigation). By applying this framework, the analysis systematically links technological adoption with Nigeria's broader goals of food security, climate adaptation, and sustainable aquaculture growth

Integration of solar-powered aeration and renewable energy.

Reliable energy for pond aeration and water pumping remains a major challenge for Nigerian fish farmers. In rural areas, grid electricity is often unreliable, and many farms rely on petrol or diesel generators that are costly to run, expose farmers to fuel price volatility, and contribute significantly to greenhouse gas emissions. Solar-powered aeration systems provide a climate-smart alternative by harnessing Nigeria's abundant sunshine to operate aerators and pumps off-grid. These systems typically combine photovoltaic (PV) panels, inverters, and battery storage to drive air compressors or pumps, ensuring a continuous supply of dissolved oxygen without reliance on fossil fuels (KPA, 2022).

a) Productivity

From a productivity perspective, solar-powered aeration improves operational efficiency and reduces production risks. Reliable aeration allows farmers to maintain higher stocking densities and prevent oxygen depletion, a common cause of mass fish mortalities in intensive systems. A case study of a commercial catfish farm that transitioned from diesel generators to a solar–battery hybrid system reported a 23% reduction in energy costs per kilowatt-hour (kWh) and projected savings of ₦60 million (US$30,000) in diesel expenses over ten years (KPA, 2022). Considering that energy accounts for 20–30% of operating costs in intensive aquaculture, such savings significantly strengthen farm profitability. Furthermore, continuous aeration enhances feed conversion efficiency and growth performance, since fish are less stressed under stable oxygen conditions. Over time, this improves both yield per hectare and return on investment (ROI), creating strong incentives for adoption.

b) Resilience/Adaptation

In terms of adaptation and resilience, solar power enhances reliability by providing continuous daytime aeration while charging batteries for night use. This stability shields farmers from catastrophic fish kills caused by generator failure, power outages, or fuel shortages. Solar systems also reduce vulnerability to volatile fuel markets, a persistent challenge in Nigeria, where rising diesel costs frequently erode profit margins. Importantly, solar technologies enable year-round operations, even in off-grid rural areas, making aquaculture viable in regions where energy infrastructure is underdeveloped. By reducing dependence on external energy sources, solar aeration strengthens the adaptive capacity of farmers, ensuring they can maintain consistent production even during periods of fuel scarcity or price spikes.

c) Mitigation

On the mitigation front, replacing diesel with solar substantially lowers on-farm carbon emissions. Each liter of diesel emits approximately 2.7 kg of CO (Jakhrani et al., 2012). A medium-sized farm burning thousands of liters annually can avert tens of tons of CO emissions per year by adopting solar aeration. Additional environmental co-benefits include the elimination of noise pollution, which improves working conditions for farmers, and the reduction of particulate air pollution, which has positive implications for community health. Beyond individual farms, widespread adoption of solar-powered aquaculture could make a measurable contribution to Nigeria's national emission reduction targets under the Energy Transition Plan (ETP) and its pledge to achieve net-zero emissions by 2060 (FGN, 2022).

d) Enabling Environment and Prospects

The adoption of solar-powered systems is further supported by a favorable policy environment. Nigeria's ETP highlights solar as a priority energy pathway, creating opportunities for integration into agriculture and aquaculture. Local entrepreneurs already market pond-scale solar aerator kits priced between ₦80,000 and ₦100,000 (FHN, 2022), and financing plans are emerging to help farmers overcome high upfront costs. Payback periods can be as short as one to two years from fuel savings alone, making adoption economically viable for small and medium-scale farmers. Expanding access through capital subsidies, tax waivers, and inclusion of solar equipment in agricultural credit schemes could accelerate uptake. International climate finance and donor programs also present opportunities to scale solar aquaculture as part of Nigeria's broader blue economy and food security agenda. Overall, solar-powered aeration is a "triple-win" CSAQ innovation. It raises productivity by enabling higher yields and efficiency, builds resilience by protecting farmers against energy supply disruptions and fuel price shocks, and contributes to mitigation by reducing greenhouse gas emissions and environmental pollution. As both policy and market conditions shift toward renewable energy integration, solar technologies stand out as one of the most scalable and impactful solutions for advancing climate-smart aquaculture in Nigeria.

Mobile Farm Management Apps and Digital Tools

Digital technology is transforming Nigerian aquaculture by moving farms from intuition-driven practices toward data-based decision-making. Mobile applications and cloud-based tools support record-keeping, feeding schedules, water quality monitoring, marketing, and advisory services. Within the CSAQ framework, these tools contribute to productivity, resilience, and mitigation.

i. Productivity Mobile apps improve efficiency by helping farmers monitor feed use, fish growth, pond conditions, and costs in real time. Feeding management is especially important: with feed accounting for 60–70% of production costs in Nigeria, small improvements in feed conversion ratio (FCR) can significantly raise profitability. Apps such as those piloted by Olam Group automatically calculate FCR and return on investment (ROI), allowing farmers to quickly spot inefficiencies like overfeeding (Olam, 2018). In East Africa, AquaRech app users (in Kenya) shortened growth cycles by 30% and reduced mortality through optimized feeding and water monitoring; results that point to strong potential in Nigeria (Catalyst Fund, 2022). Digital records also professionalize aquaculture, enabling smallholders to generate profit-and-loss statements and track trends such as which feed brand yields better growth. This not only improves farm management but also strengthens access to credit, as banks increasingly demand verifiable farm data (Fregene Ojo, 2012).

ii. Resilience/Adaptation Digital platforms enhance resilience by providing farmers with real-time feedback and adaptive management tools. Apps can recommend ration adjustments during extreme heat or early disease signs, helping farmers respond quickly to environmental and biological stresses. Virtual extension services embedded in apps connect farmers to experts via chat or video call, bridging the extension gap in states where fewer than 5% of fish farmers receive regular in-person support (Olam, 2018). Market-linkage features also make farms more resilient to price fluctuations by connecting producers directly with input suppliers and buyers, sometimes with bundled cold-chain logistics. By creating transparency and connectivity, digital tools reduce farmers' exposure to both production shocks and market risks.

iii. Mitigation Digital technologies contribute to environmental sustainability by cutting waste and nutrient pollution. Precision feeding tools reduce overfeeding, which not only saves feed but also limits excess nutrient loading in ponds that can degrade water quality and lead to higher methane and nitrous oxide emissions. By optimizing input use, apps lower the ecological footprint of aquaculture while supporting more sustainable resource management. In addition, aggregating data across farms provides policymakers and researchers with insights into production practices and environmental impacts, which can inform better climate-smart policies and extension strategies.

iv. Enabling Environment and Prospect Smartphone penetration now exceeds 50% in Nigeria, and 4G coverage is expanding, making digital aquaculture tools increasingly accessible. Socially, younger, tech-savvy farmers are more open to adoption, while economically, the low cost of apps compared with the benefits (10–15% improvements in growth efficiency reported in pilots) creates a strong business case (TBP, 2020). Policy also favors scaling: the National Agricultural Technology and Innovation Policy (NATIP 2022–2027) emphasizes digital transformation in farming. To accelerate uptake, development programs and private companies are bundling apps with feed sales, offering discounts for digital record use, or proposing micro-loans for farmers with strong digital records. These measures create the enabling conditions for Nigeria to leapfrog toward data-driven, climate-resilient aquaculture systems.

Automated Water Quality Monitoring (IoT Sensors)

Fish farming in Nigeria would greatly benefit from real-time monitoring of water conditions, as fish are highly sensitive to sudden drops in dissolved oxygen (DO) or spikes in ammonia that can cause mass mortalities within hours. Traditionally, farmers would test water occasionally or rely on observing fish behavior, but continuous monitoring was not feasible. With the Internet of Things (IoT), affordable sensor systems would make it possible to constantly track water quality and even automate responses. IoT-based systems typically include sensors for DO, pH, temperature, and ammonia, transmitting data via GSM or Wi-Fi to a farmer's phone or cloud platform (Jan et al., 2021). If parameters move outside safe ranges, farmers would receive instant alerts, such as a text message if DO drops below 4 mg/L or, in advanced setups, aerators and pumps would be triggered automatically.

a) Productivity IoT sensors would enhance productivity by reducing the risk of catastrophic fish kills, which currently can wipe out stocks worth hundreds of thousands of naira in a single event. A system costing ₦150,000 would quickly pay for itself by preventing just one such incident (Idachaba et al., 2017; Statista, 2020). Continuous monitoring would also improve feed conversion ratios (FCR); evidence shows IoT-managed ponds achieving FCRs of 1.8 compared with 2.0 in conventional ponds; roughly a 10% feed saving, equivalent to ₦100,000 per cycle for farms spending ₦1 million on feed (Idachaba et al., 2017). Over time, accumulated sensor data would reveal patterns (e.g., oxygen dips at 4 AM), enabling preventive measures that sustain fish growth and yield. AI integration would further support predictive management, identifying likely ammonia spikes in advance (Obado, 2019).

b) Resilience/Adaptation IoT systems would enhance resilience by giving farmers the ability to respond rapidly to climate-driven fluctuations such as heat waves or erratic rainfall, which exacerbate water quality problems (Chafa et al., 2021). Alerts and automated controls would ensure ponds remain within safe parameters, minimizing stress on fish and reducing mortality rates. Farmers would also be able to check water quality remotely on smartphones, saving labor and freeing time to manage more ponds or diversify their activities. As climate variability intensifies, such adaptive capacity would become increasingly vital for sustaining aquaculture.

c) Mitigation By using energy and water more efficiently, IoT systems would contribute to climate change mitigation. Aerators, for instance, would run only when DO falls below a threshold, reducing unnecessary energy use. When paired with solar power, this approach would further minimize emissions, cutting the carbon footprint of intensive farms. Additionally, smart feeding and water management would reduce excess nutrient discharge, thereby lowering methane and nitrous oxide emissions linked to overfeeding and poor pond management. Studies indicate smart aquaculture systems can reduce mortality by up to 40% and increase yields by 15–50% while conserving inputs (Abdullah et al., 2021).

d) Enabling Environment and Prospects Global IoT adoption costs are falling rapidly, with average sensor prices dropping from $.30 in 2004 to $.44 in 2018 (Statista, 2020). With 3G/4G coverage now reaching over 80% of Nigeria's population (GSMA, 2022), connectivity would no longer be a major barrier. Nigerian researchers have already prototyped locally adapted sensor systems (Chukwu Orakwue, 2018), and startups are entering the market with low-cost kits. Policy support; such as subsidies for sensor kits, training programs under the National Agricultural Technology and Innovation Policy (NATIP 2022–2027), or bundling IoT devices into credit schemes; would accelerate diffusion. In summary, IoT-enabled monitoring would embody the CSAQ "triple win": enhancing productivity through precision control and loss prevention, strengthening resilience by enabling rapid response to climate-induced water quality swings, and reducing emissions by optimizing energy and resource use. With supportive policies and falling technology costs, IoT systems would play a central role in advancing climate-smart aquaculture in Nigeria.

Biofloc Technology (BFT) for Waste Recycling and Intensive Production

Biofloc technology (BFT) is an innovative approach to aquaculture that recycles waste into valuable protein while reducing water use and environmental discharge. Instead of allowing nitrogenous waste from fish excreta and uneaten feed to accumulate as harmful ammonia, farmers foster dense microbial communities by adding a carbon source (such as molasses or cassava starch) to stimulate heterotrophic bacteria. These microbes form protein-rich "flocs," suspended in the water by aeration, which fish consume as supplementary feed (Jamal et al., 2020). BFT contributes simultaneously to the three pillars of the Climate-Smart Aquaculture (CSAQ) framework; enhancing productivity, building resilience, and reducing environmental impacts.

a) Productivity BFT reduces feed requirements (the single largest cost in aquaculture) by converting waste into edible microbial protein. Studies show that feed inputs decline by 20–30% in biofloc systems (Ray et al., 2017). In catfish production, for example, feed conversion ratios (FCR) improve from 2.0 in clear-water tanks to about 1.5–1.7 in biofloc tanks (Babatunde et al., 2021). This translates into substantial cost savings, higher profitability, and reduced dependence on imported fishmeal. In addition, BFT enables higher stocking densities; often two to three times greater than conventional systems, with yields of 20–30 kg/m³ compared to extensive methods (Diatin et al., 2021). The result is significantly more fish produced per unit of land and water, improving farmers' incomes and contributing to food security.

b) Resilience/Adaptation Biofloc systems enhance resilience by drastically reducing water use; by 70–90% compared to traditional ponds (Ogello et al., 2021). The microbial community detoxifies the water and reduces the need for exchange, which conserves scarce resources during dry seasons and in arid regions of Nigeria. Limited water exchange also improves biosecurity, as pathogens are less likely to enter the system, while the probiotic effect of beneficial microbes strengthens fish immunity and stress tolerance (Kumar et al., 2021). Farmers therefore experience fewer disease outbreaks and greater survival rates, making their operations more climate-resilient.

c) Mitigation BFT mitigates environmental impacts by reducing nutrient-rich effluent discharge, which otherwise contributes to eutrophication of natural waters. By recycling nitrogenous waste into microbial protein, the technology lessens dependence on fishmeal, thereby lowering the carbon footprint of feed production. With sufficient aeration; ideally powered by renewable energy such as solar, BFT also avoids greenhouse gas emissions linked to poor water management. In this way, biofloc integrates circular economy principles: turning waste into feed while reducing pollution.

d) Enabling Environment and Prospects In Nigeria, adoption of BFT remains limited to innovative farmers, particularly intensive hatcheries and tank operators. However, rising feed costs, limited water resources, and government goals for import substitution make it increasingly attractive. Expanding adoption will require training on biofloc culture management, provision of affordable aeration equipment, and demonstration projects to build farmer confidence. With appropriate policy and technical support, BFT offers a practical pathway toward more productive, resilient, and environmentally sustainable aquaculture.

Integrated Aquaponics Systems

Aquaponics integrates aquaculture with hydroponic crop production in a closed-loop system. Fish are raised in tanks, and their nutrient-rich wastewater is circulated to hydroponic plant beds. Bacteria convert the fish waste into plant fertilizer, which is taken up by crops, and the cleansed water is returned to the fish tanks (Lennard Goddek, 2019). This design produces both fish and vegetables with drastically reduced water use and minimal waste discharge. Studies show aquaponics can cut water use by up to 90% compared to separate fish and soil farming, as water is continuously recirculated (Obirikorang et al., 2021). In Nigeria, where water scarcity in the north and population density in cities are pressing issues, aquaponics offers a pathway to produce protein and vegetables efficiently in constrained environments.

a) Productivity Aquaponics increases productivity by diversifying outputs, yielding both fish and vegetables in the same system. A small backyard unit (1,000 L tank with 10 m² of plant beds) can produce tens of kilograms of fish and hundreds of kilograms of vegetables annually, supporting household nutrition and generating surplus for sale (FAO, 2014). Urban entrepreneurs in Lagos and Abuja are already using aquaponics to serve premium markets, where organically grown produce fetches higher prices. Because plants act as biofilters, expensive water treatment inputs are avoided, and farmers essentially receive an "organic fertilizer" for free. Profitability can be high: one study found aquaponics returns up to 30 times more profit per unit area than conventional agriculture due to dual outputs and efficient space use (Benjamin et al., 2020). The use of controlled environments such as greenhouses also allows year-round production, smoothing supply and income despite seasonal climate variability (Proksch et al., 2019).

b) Resilience/Adaptation By decoupling production from soil and open water bodies, aquaponics enables farming in areas unsuitable for conventional agriculture, including polluted urban land and regions with poor soil quality. This makes it particularly valuable for food security in climate-stressed northern Nigeria. The closed-loop design conserves scarce water resources and shields production from erratic rainfall or drought, while greenhouse-based systems reduce vulnerability to flooding and heat stress. In the Near East and North Africa region, integrated agri-aquaculture (including aquaponics) has proven effective in conserving water and producing food in desert conditions (FAO, 2018). Nigeria's arid northern states could similarly benefit from aquaponics units in communities with limited freshwater. Aquaponics also contributes to household resilience by improving dietary diversity; providing both protein and vegetables from the same system. Local pilot projects, such as SANFU, show aquaponics can enhance food security and household income even for small-scale farmers, underscoring its potential in resource-limited contexts.

c) Mitigation Aquaponics minimizes environmental impacts by preventing nutrient-rich effluent discharge into waterways, thereby reducing eutrophication risks. Since fish waste provides nutrients for crops, the system often eliminates the need for synthetic fertilizers, lowering associated emissions. If powered by renewable energy, aquaponics can operate with a near carbon-neutral footprint. Moreover, by intensifying production on small plots, aquaponics reduces the need to convert additional land for farming, helping conserve ecosystems.

d) Enabling Environment and Prospects Two aquaponics designs exist: coupled systems, which recirculate water in a single loop, and decoupled systems, where fish and plant loops are semi-independent. Coupled systems dominate small farms in Nigeria due to their simplicity, while decoupled systems offer greater optimization potential for larger enterprises (Benjamin et al., 2020; Obirikorang et al., 2021). As costs decline and local expertise improves, aquaponics could be scaled through community-level projects such as school-based units or cooperative farms. Policy measures; such as grants, soft loans for startups, and targeted training programs; would accelerate adoption. By boosting productivity, strengthening resilience, and reducing environmental impacts, aquaponics aligns closely with Nigeria's Blue Economy and urban agriculture strategies.

Recirculating Aquaculture Systems (RAS)

Recirculating Aquaculture Systems (RAS) are advanced tank-based systems where water is continually filtered, sterilized, and reused, creating a controlled and bio-secure environment for high-density fish culture (Helfrich Libey, 2013). With over 90–99% of water recirculated, RAS use less than 5–10% of the water required by open systems, while allowing precise regulation of temperature, oxygen, and pH (Bregnballe, 2015). Nigeria has recently begun piloting RAS to address land and water constraints, with feasibility studies confirming technical viability for both commercial-scale farms and smaller peri-urban units (Benjamin et al., 2022).

a) Productivity RAS achieve some of the highest yields in aquaculture, reaching 50–100 kg of fish per cubic meter of water (Benjamin et al., 2022). By providing stable, optimal growth conditions year-round, farmers can run multiple production cycles, shorten grow-out times, and diversify into high-value or export species. For example, tilapia grown in intensive RAS can reach 1 kg in six months, compared to 8–10 months in ponds (Agossou, 2021). RAS also reduce land footprints, enabling profitable fish farming in space-constrained urban settings. Although capital-intensive, modular and downscaled RAS designs (e.g., 5 tons/year capacity in greenhouses) create opportunities for medium-scale enterprises and peri-urban entrepreneurs.

b) Resilience/Adaptation RAS buffer production against external shocks such as droughts, floods, or disease outbreaks that typically threaten open systems (INN, 2021). Because the systems are enclosed, fish are shielded from extreme rainfall events that cause pond overflows, escapes, or pathogen introductions. Biosecurity is stronger, preventing disease entry and escapes of farmed species. This stability allows farmers to operate in arid regions or urban areas with poor soil or limited water, expanding the geographic range of aquaculture. IoT sensors and automation further strengthen resilience by monitoring dozens of parameters in real time, alerting farmers to problems such as pump failures or CO buildup before catastrophic losses occur.

c) Mitigation RAS minimize effluent discharge by concentrating wastes in filters that can be composted into fertilizer or used in biogas systems, reducing nutrient pollution of natural waters. Energy requirements are high due to aeration and pumping, but efficiency gains—such as waste heat recovery and renewable energy integration—can reduce the footprint. Pairing RAS with solar or hybrid energy systems makes them far more climate-friendly. By maximizing feed utilization and limiting environmental discharge, RAS embody sustainable intensification principles, achieving high outputs with contained impacts.

d) Enabling Environment and Prospects In Nigeria, uptake of RAS is currently limited to well-financed commercial farms and research institutions, but the technology is recognized in aquaculture policy as a pathway for intensification without proportional increases in water or land use. Scaling RAS will require skilled technicians, soft loans, and tax incentives for equipment, alongside demonstration farms. Even if not every farmer adopts full RAS, elements such as partial biofilters or small tank systems for fry nursing can diffuse climate-smart practices across the sector. With supportive policies and renewable energy integration, RAS stand out as a technology capable of delivering the CSAQ "triple win": high productivity, resilience to climate shocks, and environmental sustainability.

The combination, the technological innovations discussed above form a toolkit for advancing climate-smart, integrated aquaculture in Nigeria. They are not mutually exclusive; in fact, they complement one another. Solar power can offset the high energy needs of RAS and biofloc systems, while IoT sensors can be applied across biofloc ponds, aquaponics, or RAS units to optimize water quality and feeding practices. Together, these synergies demonstrate how multiple innovations can converge to deliver greater productivity, resilience, and environmental sustainability than any one technology alone. A forward-looking vision might be a solar-powered urban aquafarm that integrates RAS and aquaponics under IoT/AI control; producing fish and vegetables with minimal land and water, powered by renewable energy, and operating with near-zero waste. While such models are niche today, they illustrate the direction of sustainable aquaculture development in Nigeria. Just as mobile phones rapidly transitioned from luxury to necessity, the diffusion of these technologies could follow a similar trajectory as costs decline and local expertise grows. International knowledge transfer-from China's rice–fish systems to Europe's advanced RAS facilities—also offers lessons that Nigeria can adapt to its own context, potentially leapfrogging into modern practices while avoiding the missteps of early adopters elsewhere.

Having established how these innovations align with the CSAQ framework, the next section applies Institutional Theory to analyze how Nigeria's policies and governance structures may either accelerate or constrain the transition to climate-smart, integrated fish farming.

e) Institutional Barriers and Enablers in Policy Analysis for Climate-Smart Integrated Aquaculture in Nigeria Climate-smart aquaculture (CSAq) offers Nigeria a unique opportunity to expand fish production, strengthen resilience, and reduce environmental impacts in line with national food security and climate commitments. However, adoption of CSAq technologies such as biofloc, aquaponics, recirculating aquaculture systems (RAS), IoT-based monitoring, and solar-powered aeration remains limited. These constraints are not merely technical or economic; they are deeply rooted in the institutional environment that shapes farmers' choices, perceptions, and opportunities. This section applies Institutional Theory and the Diffusion of Innovations (DOI) theory to examine barriers and enablers for climate-smart integrated aquaculture in Nigeria. Institutional Theory highlights how regulative (laws and policies), normative (standards and professional roles), and cognitive (legitimacy and shared perceptions) pillars structure opportunities and constraints (Scott, 2005). Change in these pillars, whether through reforms, professionalization, or shifts in legitimacy; is essential for scaling CSAq. DOI complements this by explaining how adoption is shaped by perceptions of relative advantage, compatibility, complexity, trialability, and observability (Rogers, 2003). Taken together, these perspectives reveal not only where barriers lie, but also what forms of institutional change and adoption dynamics are needed to accelerate CSAq diffusion.

1) Financial Barriers: Institutional Constraints to Technology Adoption
One of the most persistent obstacles to CSAq adoption in Nigeria is access to finance. While technologies such as solar-

powered aerators, sensor networks, and small-scale RAS units offer long-term cost savings, they require upfront investment that most farmers cannot afford. i) Institutional Theory perspective. At the regulative level, Nigeria's banking system creates structural exclusion. Interest rates frequently exceed 20% and collateral requirements remain onerous (Azeez et al., 2022). Such frameworks prioritize risk minimization over sectoral innovation, effectively locking out small-scale fish farmers who dominate production and operate with minimal working capital (Falola et al., 2022). Regulative change would involve concessional credit lines, guarantee schemes, or subsidized insurance products that de-risk aquaculture lending. At the normative level, banking practices continue to view aquaculture as marginal and high-risk, with little institutional effort to create sector-specific loan products. Normative change would require professionalization within the financial sector, where bankers are trained to recognize aquaculture's potential and design lending instruments tailored to its cycles. At the cognitive level, both farmers and lenders perceive aquaculture as inherently risky, reinforcing aversion to debt-financed innovation. The absence of aquaculture insurance deepens these perceptions. Cognitive change would require legitimizing aquaculture as a "bankable" sector through success stories, repayment records, and insurance-backed financing models. ii) DOI perspective. Financial barriers distort farmers' perceptions of innovations' relative advantage, as immediate debt risk overshadows potential long-term gains. Limited credit reduces trialability (few can pilot systems like biofloc tanks or IoT sensors) and suppresses observability (fewer visible success cases). Perceived complexity of financial products, combined with uncertainty, deters engagement. Unless financial institutions evolve, diffusion will remain confined to innovators rather than spreading to the early majority. Feed costs, which constitute 60–70% of total production expenses, exacerbate financial pressures. Prices have risen by more than 1,000% since 2010 due to inflation and reliance on imported inputs (FCWC, 2018; FAO, 2020). With limited liquidity, farmers remain trapped in low-investment, low-yield systems. Overcoming this requires integrated financial reforms that tackle regulative, normative, and cognitive barriers while improving adoption incentives.

2) Institutional and Knowledge Barriers: Normative and Cognitive Weaknesses

Even where finance is available, weak knowledge systems and underdeveloped support services hinder CSAq adoption. i) Institutional Theory perspective. At the normative level, Nigeria's extension system is underdeveloped. Less than 5% of farmers receive regular government support (Subasinghe et al., 2021), and many officers lack expertise in advanced aquaculture technologies (Adeleke et al., 2020). Private providers; feed companies, NGOs, producer associations; fill gaps, but services remain fragmented (Skretting, 2020). Normative change would require professionalizing aquaculture extension, embedding CSAq into training curricula, and scaling farmer field schools and innovation clusters. At the cognitive level, weak RD undermines legitimacy and adaptability of innovations. Technologies are often imported, raising costs and limiting contextual relevance (FAO, 2020). Farmers lack experiential knowledge or mental models to validate practices such as biofloc or RAS. Cognitive change requires participatory RD, locally adapted designs, and demonstration farms across ecological zones to normalize new systems. Weak supporting infrastructure further constrains adoption. Cold chain and transport limitations discourage intensification, as productivity gains risk being wasted due to gluts or spoilage. Institutional change here requires aligning production innovations with investments in downstream infrastructure. ii) DOI perspective. Knowledge gaps stall farmers in the knowledge and persuasion stages of adoption. Innovations appear complex without adequate training, while limited demonstrations reduce observability. Lack of pilot opportunities suppresses trialability, and where systems clash with existing practices, compatibility is perceived as low. Even when potential advantages exist, adoption slows because innovations are not seen as credible or practical within farmers' contexts.

3) Regulatory and Policy Barriers: Misaligned Regulative Institutions
Policy and regulatory frameworks also constrain CSAq. i) Institutional Theory perspective. At the regulative level, outdated strategies have created vacuums. The National Aquaculture Strategy (2008) was never updated during years of rapid growth (FMARD, 2008). Current regulations neither mandate effluent treatment nor incentivize RAS or biofloc systems, while tariffs on essential inputs (solar panels, pumps, meters) increase costs (World Bank, 2017). Absence of quality standards for inputs allows substandard equipment to circulate, eroding trust. Governance fragmentation across agriculture, power, and water ministries creates incoherence (FMARD, 2015; FMWR, 2016; TTID, 2021). Enforcement capacity remains weak; expansion of production volumes has been prioritized over sustainability (FAO, 2020). Land tenure ambiguity further complicates integrated practices such as rice–fish farming. Regulative change would involve regular policy updates, environmental safeguards, certification systems, inter-ministerial coordination, and land-use reforms. ii) DOI perspective. Regulatory voids reduce relative advantage (modernization is costly, benefits uncertain) and compatibility (policies do not align with farmer realities). Weak enforcement eliminates authority-based adoption triggers, meaning; farmers can ignore sustainability practices without consequence. Circulation of substandard inputs damages observability by generating negative experiences that discourage diffusion. Without supportive regulation, CSAq remains an option, not a norm.

4) Enabling Factors and Recent Progress: Emerging Institutional Supports
Despite significant barriers, Nigeria's aquaculture sector has seen positive institutional evolution across all three pillars, creating better conditions for CSAq adoption. i) Financial support initiatives. The Anchor Borrowers' Programme (ABP) has extended credit to smallholders, improving working capital (CBN, 2021). Donor programs such as World Bank Fadama and IFAD's VCDP have offered co-financing and grants (Worldfish, 2022b). NGO-led pilots (e.g., PIND) show that cooperative lending can achieve near-100% repayment (PIND, 2019). These represent regulative change (credit programs), normative change (group-based accountability), and cognitive change (proving aquaculture is bankable). From a DOI perspective, they improve trialability (financing pilots), observability (peer success), and relative advantage (reduced capital costs). ii) Institutional strengthening. NATIP (2021–2027) emphasizes sustainability, digital innovation, and adaptive research, strengthening the regulative pillar. Research institutes and universities have piloted CSAq systems, acting as demonstration hubs. These build normative standards and cognitive legitimacy, while enhancing observability and reducing complexity for farmers. iii) Regulatory incentives. Tariff waivers on solar panels and RAS equipment (TTID, 2021), discussions of green finance, and stricter pollution controls indicate emerging regulative shifts. Proposed eco-certification schemes combine normative and market incentives. From a DOI lens, this strengthens relative advantage (cheaper tech, higher-value products) and creates authority-based adoption triggers. iv) Market dynamics. Nigeria's persistent fish deficit, urban demand for premium products, and pandemic-driven adoption of e-commerce platforms (Agbeja Oluyede, 2020) represent cognitive change—new norms legitimizing CSAq. From a DOI perspective, visible market successes enhance observability and compatibility with emerging consumer expectations.

5) Summary and Strategic Outlook
Institutional Theory reveals that CSAq adoption is constrained by misaligned regulative frameworks, weak normative systems, and limited cognitive legitimacy. DOI shows how these institutional weaknesses translate into adoption barriers, dampening perceptions of relative advantage, compat-

ibility, trialability, and observability. Together, the theories clarify why adoption has been slow, even where technical and economic benefits are evident. At the same time, enabling factors; financial reforms, professionalized extension, regulatory incentives, and shifting market expectations; demonstrate that institutional change is already underway. These changes strengthen regulative frameworks (e.g., tariff waivers, credit programs), normative expectations (e.g., farmer clusters, innovation standards), and cognitive legitimacy (e.g., demonstration hubs, consumer demand for quality). They also create favorable adoption conditions: innovations become less risky, more visible, and better aligned with farmer and market needs. The challenge is to consolidate these shifts into a coherent strategy. This requires managing institutional change; through regulatory reform, normative standard-setting, and cognitive legitimation; while simultaneously addressing adoption dynamics with demonstrations, pilot schemes, and certification. If pursued strategically, Nigeria can move CSAq from the margins to the mainstream, bridging its 2.5-million-ton fish deficit, strengthening climate resilience, and advancing sustainable aquaculture.

Conclusion and Recommendations Nigeria stands at a critical crossroads in aquaculture development. Integrated fish farming, enhanced with climate-smart innovations, presents a viable pathway to increase domestic fish production sustainably, strengthen resilience to climate change, and advance national development goals. The evidence shows that technologies such as solar energy, precision feeding, IoT monitoring, biofloc, aquaponics, and RAS can significantly improve efficiency and environmental performance. Solar-powered systems reduce energy costs and emissions, IoT-enabled precision feeding lowers feed waste and mortality, while biofloc, aquaponics, and RAS reduce water use while boosting yields. Together, these outcomes align directly with Nigeria's ambitions for fish self-sufficiency, food security, and climate adaptation. Yet, as Diffusion of Innovation (DOI) theory emphasizes, adoption depends not only on technical merit but also on how farmers perceive innovations; their relative advantage, compatibility with existing practices, complexity, opportunities for trialability, and the observability of results. Current adoption barriers, i.e. financial, institutional, and regulatory; slow diffusion across these dimensions. The following recommendations therefore combine policy interventions with strategies that directly strengthen the adoption process.

1. Increase Access to Finance and Incentivize Green Investment

Government and financial institutions should design aquaculture-specific financial products that de-risk investment. Options include low-interest innovation loans, credit guarantees, and targeted grants for technologies such as solar aerators, water-quality sensors, or biofloc tanks. For instance, subsidizing the first 500 solar aerators could create early observability effects, showcasing measurable benefits to peers. Tax and duty waivers; already applied to solar panels, should be extended to aquaculture equipment to improve relative advantage by reducing costs. Successful microfinance models, such as PIND's group-lending schemes, illustrate how collective accountability enhances repayment. Embedding such models within the Anchor Borrowers' Programme or Bank of Agriculture could improve compatibility by aligning new financial instruments with farmers' cooperative structures. Finally, leveraging international climate finance (e.g., Green Climate Fund or Blue Economy bonds) can expand concessional lending, reducing perceived complexity of financial products by offering bundled technical assistance.

2. Strengthen Institutional Support, Research, and Extension

Building farmer capacity and confidence is essential to reduce perceived complexity and strengthen persuasion stages of adoption. The National Agricultural Technology and Innovation Policy (NATIP 2022-2027) should be operationalized through dedicated aquaculture innovation centers in major production clusters. These hubs, staffed by trained extension specialists-can demonstrate biofloc management, aquaponics design, and IoT-enabled water monitoring. Farmer field schools should guide participants through full production cycles, enhancing trialability by allowing farmers to test new systems under supervision. Adaptive research collaborations between universities, NIFFR, and producer groups should focus on local adaptation (e.g., biofloc using cassava waste), ensuring compatibility with local contexts. South-South partnerships with countries such as Indonesia (biofloc) or Vietnam (integrated rice-fish) can expand training, while returnee technicians can champion innovations domestically. Such exchanges enhance observability, as farmers witness real-world applications of technologies under similar conditions.

3. Enhance Regulatory Frameworks and Policy Integration
Nigeria's forthcoming National Fisheries and Aquaculture Policy should explicitly embed climate-smart objectives e.g., "50% of medium-to-large farms adopt at least one climate-smart innovation by 2030." Regulative measures can stimulate diffusion by shifting adoption from voluntary to normative: Mandating environmental management plans for large farms can push adoption of biofloc or RAS, enhancing relative advantage by linking compliance with cost savings. Streamlining licensing for integrated systems improves compatibility, reducing bureaucratic obstacles. Introducing voluntary eco-certification schemes provides market rewards for adopters, strengthening observability through certification labels and trialability by allowing phased compliance. Policy alignment with Nigeria's Blue Economy and climate frameworks will ensure CSAq is recognized as both an environmental necessity and an economic opportunity.

4. Facilitate Market Development and Value Chain Support
Market and value-chain investments can reinforce adoption by making benefits more visible and profitable. Cold storage, processing, and logistics facilities, particularly solar-powered cold rooms in production clusters will minimize post-harvest losses and demonstrate relative advantage of intensified production. Digital platforms and cooperatives should be supported to expand farmers' market access, reinforcing compatibility with existing trading systems while accelerating observability of successful adopters. Public campaigns promoting the nutritional and environmental benefits of sustainably farmed fish can also influence consumer perceptions, indirectly strengthening farmer adoption. Supporting SMEs in feed, hatcheries, and processing will create an ecosystem of service providers, reducing complexity for farmers who often lack direct access to inputs or technical services. Promoting local insect-based feed production will cut costs, further enhancing the relative advantage of climate-smart systems.

5. Pilot Projects and Phase-Wise Scale-Up
Diffusion theory emphasizes the importance of early demonstrations in accelerating uptake. Nigeria should adopt a phased scale-up strategy: • Phase 1 (Piloting, 2023-2025): Establish integrated pilot farms in different agro-ecological zones, subsidize early adopters, and use these as training hubs. This increases trialability and observability by providing tangible proof of benefits. • Phase 2 (Scaling Up, 2025-2027): Expand adoption once results show clear relative advantage (e.g., 20% energy savings from solar aeration, 30% yield gains from biofloc). Embed PPP models to distribute risks and benefits. • Phase 3 (Mainstreaming, 2027-2030): Institutionalize CSAq through extension curricula, sustainability mandates (e.g., effluent treatment), and domestic equipment industries. This embeds compatibility by integrating CSAq into routine practice.

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