

**CLIMATE SMART ACTIONS (CSA) AQUACULTURE, AGROFORESTRY
AND RESOURCES MANAGEMENT**

GLOBAL ISSUES & LOCAL PERSPECTIVES

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Global Issues & Local Perspectives

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Preface

This book adopts an exegetical approach as well as a pedagogic model, making it attractive agriculture and environmental economics teachers, professional practitioners and scholars. It eschews pedantry and lays bars the issues in such clarity that conduces to learning. The book elaborates on contemporaneous **Climate smart actions (CSA) aquaculture, agroforestry and resources management** issues of global significance and at the same time, is mindful of local or national perspectives making it appealing both to international and national interests. The book explores the ways in which **Climate smart actions (CSA) aquaculture, agroforestry and resources management** issues are and should be presented to increase the public's stock of knowledge, increase awareness about burning issues and empower the scholars and public to engage in the participatory dialogue **Climate smart actions (CSA) aquaculture, agroforestry and resources management** necessary in policy making process that will stimulate increase in food production and environmental sustainability. **Climate smart actions (CSA) aquaculture, agroforestry and resources management : *Global Issues & Local Perspectives*** is organized in three parts. Part One deals with The Concept of **Climate smart actions (CSA)**, Part Two is concerned with The Concept of **aquaculture**, and Part Three deals with the Concept of **agroforestry and resources management**

Eteyen Nyong; March 2026

Chapter 12:

Rice-Fish Integration Systems: Climate-Smart Innovation for
Sustainable Food Security and Livelihood Enhancement in Nigeria.

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1.0 INTRODUCTION

1.1 Global Context and Food Security Challenges

The global agricultural sector confronts unprecedented challenges threatening food security for billions worldwide. With world population projected to reach 9.7 billion by 2050, agricultural systems must increase food production by 70% while addressing climate change, resource depletion, and environmental degradation (Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S. E., Srinath Reddy, K., Narain, S., Nishtar, S., & Murray, C. L. J., 2019). This challenge is acute for rice and fish production systems providing nutritional sustenance for over half of humanity.

The Rice Production Challenge: Rice serves as primary staple food for more than 3.5 billion people globally, providing approximately 20% of the world's dietary energy supply (Gul, S., Shafiq, U., Mir, S. A., Iqbal, G., & Lone, H. Q., 2024). However, conventional rice monoculture faces critical sustainability constraints: consuming 30-40% of global irrigation water, emitting substantial methane contributing 10-30% of agricultural greenhouse gas emissions (Gupta, K., Kumar, R., Baruah, K. K., Hazarika, S., Karmakar, S., & Bordoloi, N., 2021), experiencing declining soil fertility, demonstrating increasing vulnerability to climate extremes, and facing mounting pest pressures (Naseer, A., Mustafa, N., Iftikhar, S., Fareed, Z. U. H., Bashir, W., Khan, K., Batool, I., Zafar, I., Ali, U., & Ather, N., 2024).

Evidence from Indian rice fields indicates methane emissions range from 2.7 to 6.4 Tg CH₄ year⁻¹, with four states as emission "hot spots" accounting for 53.9% of total emissions (Gupta *et al.*, 2021). Nitrous oxide emissions can reach 9.11 kg ha⁻¹ under intensive management, with 298 times the global warming potential of carbon dioxide (Gupta *et al.*, 2021).

The Aquaculture Expansion Dilemma: Aquaculture has transformed into the fastest-growing food production system, now providing over 50% of fish consumed worldwide (Gul *et al.*, 2024). However, rapid growth has brought environmental concerns including habitat destruction, disease outbreaks, water quality degradation, and resource competition with agriculture.

Nutrition Security Integration: Food security cannot be achieved without nutrition security, which requires access to diverse macro- and micronutrients essential for health (Hwalla, N., El Labban, S., & Bahn, R. A., 2016). The relationship is complex—low-income families may maximize limited resources by consuming low-cost, energy-dense foods instead of nutrient-dense options, resulting in nutrition insecurity despite caloric abundance (Hwalla *et al.*, 2016).

The Problem Statement: The fundamental challenge is how to substantially increase production while reducing environmental impacts, enhancing climate resilience, improving nutrition, and strengthening farmer livelihoods. Conventional approaches treating rice and fish as separate systems have reached sustainability limits.

Rice-Fish Integration as Solution: Rice-fish farming systems offer integrated solutions by cultivating fish within rice paddies, creating mutually beneficial relationships (Obiero, K., Ogello, E., Munguti, J., Mboya, J., Kyule, D., Opiyo, M., Githukia, C., Ouko, K., Kembanya, E., Abwao, J., Matolla, G., Ani, J., Sambu, S., Cheserek, M., Ngeno, K., Khobondo, J., Meenakshisundaram, M., Tanga, C., & Yossa, R., 2024; Freed, S., Barman, B., Dubois, M., Flor, R. J., Funge-Smith, S., Gregory, R., Hadi, B. A. R., Halwart, M., Haque, M., Jagadish, S. V. K., Joffre, O. M., Karim, M., Kura, Y., McCartney, M., Mondal, M., Nguyen, V. K., Sinclair, F., Stuart, A. M., Tezzo, X., Yadav, S., & Cohen, P. J., 2020). Fish provide biological pest control, nutrient cycling, soil aeration, and weed suppression. Rice provides fish habitat, food resources, and temperature moderation (Dubois, M. J., Akester, M., Leemans, K., Teoh, S. J., Stuart, A., Thant, A. M., San, S. S., Shein, N., Leh, M., Moei, P. M., & Radanielson, A. M., 2019; Naseer *et al.*, 2024). These systems represent 2,000+ years of traditional knowledge now optimized through modern innovations (Obiero *et al.*, 2024).

1.2 Climate-Smart Agriculture Framework

Climate-smart agriculture provides a comprehensive framework with three objectives: sustainably increasing productivity and incomes, enhancing resilience to climate change, and reducing greenhouse gas emissions (Obiero *et al.*, 2024).

Alignment with Climate-Smart Principles: Rice-fish systems align exceptionally with all three pillars, achieving 10-64% productivity gains over monocultures (Obiero *et al.*, 2024; Dubois *et al.*, 2019). They reduce methane emissions by 20-64% through enhanced soil oxygenation and decrease pesticide applications by 50-90% through biological control (Naseer *et al.*, 2024; Gupta *et al.*, 2021). Economic analyses show 20-85% income increases for integrated farmers (Gul *et al.*, 2024; Dubois *et al.*, 2019).

Myanmar trials demonstrated 25% increased gross profit margins with fish production averaging 700-940 kg ha⁻¹ without compromising rice yields (Dubois *et al.*, 2019).

1.3 African and Nigerian Context

Africa's Rice Import Dependency: Africa imports over 14 million tonnes of rice annually, valued at \$6 billion, despite vast agricultural potential (Gul *et al.*, 2024).

Nigeria's Rice Sector: Nigeria cultivates 3.7 million hectares producing 8.4 million tonnes annually, yet productivity remains low at 2.3 tonnes per hectare versus Asian averages exceeding 4.5 tonnes per hectare (Gul *et al.*, 2024). Energy analysis reveals total inputs of 14,000-15,000 MJ ha⁻¹, with fertilizers contributing 73-77% and indicating low mechanization (Kosemani and Bamgboye, 2020). Profitability varies by system: swamp (29.37% return), lowland (20.10%), and upland (13.03%), with labour constituting 72-76% of costs (Chidiebere-Mark, N., Ohajianya, D., Obasi, P., & Onyeagocha, S., 2019).

Nigerian rice farming faces water scarcity, climate variability, severe pest pressure, soil degradation, and 30-40% post-harvest losses (Gul *et al.*, 2024; Kosemani and Bamgboye, 2020).

Nigeria's Aquaculture: Production reaches 380,000 tonnes annually, dominated by African catfish, but faces high feed costs (60-70% of expenses), disease outbreaks, and quality fingerling shortages (Gul *et al.*, 2024).

Integration Opportunity: Rice-fish integration can simultaneously address both sectors' challenges (Gul *et al.*, 2024; Dubois *et al.*, 2019). Despite indigenous practices, modern integration remains absent from mainstream agriculture. Adaptation potential is substantial given expanding cultivation areas, diverse agroecological zones, growing aquaculture capacity, and strong policy support (Gul *et al.*, 2024).

1.4 Chapter Objectives

This chapter analyzes rice-fish farming as climate-smart innovation to:

- Evaluate productivity, adaptation, and mitigation benefits versus monoculture.
- Review sustainable practices including microbiome modulation and precision nutrition;
- Examine environmental stress mitigation;
- Explore breeding innovations for climate resilience;
- Assess integrated disease control;
- Analyze renewable energy integration;
- Evaluate water quality management;
- Present case studies demonstrating performance;
- Identify Nigerian adoption opportunities with strategic recommendations for scaling across agroecological zones.

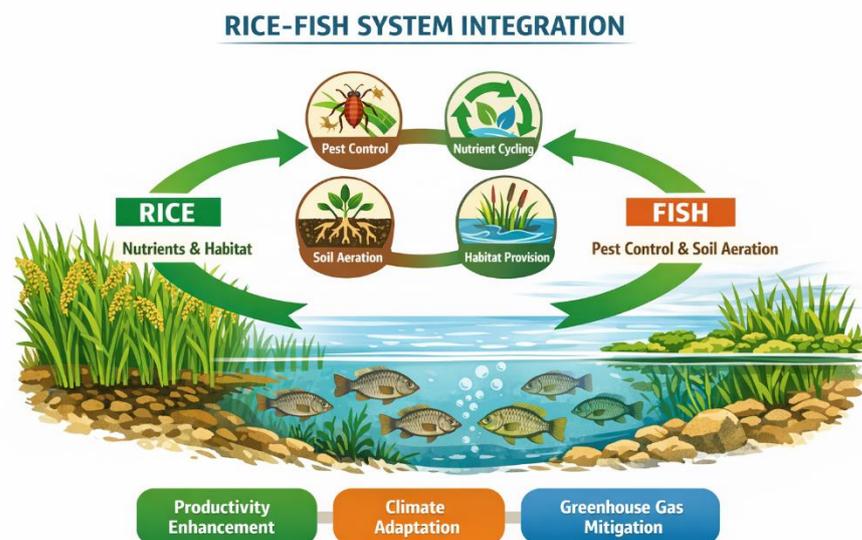


Fig 1: Conceptual framework diagram showing rice-fish system integration with bidirectional arrows indicating benefits flowing between rice and fish components. Include ecosystem services (pest control, nutrient cycling, soil aeration, habitat provision) and alignment with three climate-smart agriculture pillars.

2.0 SYSTEM BENEFITS AND CLIMATE RESILIENCE

2.1 Productivity Enhancement Through Ecological Synergies

Rice-fish integration substantially increases total system productivity through ecological complementarity and resource-use efficiency (Obiero *et al.*, 2024). Integrated systems demonstrate Land Equivalent Ratios of 1.10 to 1.64, indicating 10-64% more output per unit land area than separate monocultures (Obiero *et al.*, 2024). Rice yields in well-managed systems typically maintain 95-105% of monoculture levels, with some showing 5-15% increases attributed to improved nutrient cycling and biological pest control (Naseer *et al.*, 2024).

Fish yields vary substantially by stocking density, species, management intensity, and duration, typically ranging from 150 to 1,500 kg ha⁻¹ in traditional extensive systems (Obiero *et al.*, 2024). Intensively managed systems with supplemental feeding can reach 2,000-3,000 kg ha⁻¹ without compromising rice production (Naseer *et al.*, 2024). Myanmar trials achieved 700-940 kg ha⁻¹ fish production with rice yields maintained at 4.85 Mg ha⁻¹ using only 13% of field area for fish refuge (Dubois *et al.*, 2019).

Productivity gains arise from ecological mechanisms operating simultaneously (Naseer *et al.*, 2024). Fish excrete 80-90% of consumed nitrogen as ammonia, directly absorbed by rice roots. Isotope tracing shows 20-40% of rice nitrogen originates from fish excreta, reducing synthetic fertilizer requirements by 20-50% while maintaining yields (Naseer *et al.*, 2024; Obiero *et al.*, 2024).

Fish provide comprehensive biological pest control, consuming stem borers, planthoppers, leaf folders, and invasive golden apple snails. Field studies document 30-70% pest population reductions in rice-fish systems, enabling 50-90% decreases in pesticide application with associated cost savings and environmental benefits (Naseer *et al.*, 2024; Obiero *et al.*, 2024).

Beyond yield quantities, integration enhances nutritional security through complementary outputs addressing multiple malnutrition dimensions (Gul *et al.*, 2024). Rice provides carbohydrates (7-8% protein), while fish are protein-rich (15-25% protein) with essential amino acids. Fish provide bioavailable micronutrients including iron, zinc, calcium, vitamin A, and omega-3 fatty acids commonly deficient in rice-dependent diets (Hwalla *et al.*, 2016; Gul *et al.*, 2024).

2.2 Climate Adaptation and Risk Management

Rice-fish systems enhance resilience through multiple mechanisms buffering against climate variability and extreme events (Obiero *et al.*, 2024). Integration distributes climate risk across production pathways with differential environmental sensitivities (Naseer *et al.*, 2024). When rice suffers heat stress during flowering, fish may thrive if water quality is maintained. Conversely, if water quality temporarily deteriorates affecting fish, rice can still produce grain (Naseer *et al.*, 2024).

Field studies show rice-fish farming households experience substantially less income variability across years than rice monoculture households, indicating greater economic stability under climate variability (Obiero *et al.*, 2024). Deeper water depth maintained for fish culture (15-25 cm versus 5-10 cm in conventional paddies) provides significant thermal buffering (Naseer *et al.*, 2024).

Field measurements document 2-4°C water temperature reductions during heat waves in rice-fish paddies, protecting rice from temperature-induced spikelet sterility and fish from thermal stress mortality (Naseer *et al.*, 2024; Obiero *et al.*, 2024). Rice canopy provides beneficial shade reducing water surface temperatures during extreme heat, increasing fish survival versus open pond aquaculture exposed to direct solar radiation (Naseer *et al.*, 2024).

While rice-fish systems require adequate water, integration improves water productivity by 60-130%, producing both rice grain and fish protein rather than rice alone (Naseer *et al.*, 2024; Obiero *et al.*, 2024). This enhanced water-use efficiency is critical where competition for freshwater intensifies under climate change (Gul *et al.*, 2024).

Rice-fish paddies support 2-3 times more beneficial organism species than conventional monocultures, including predatory insects, parasitoids, pollinators, and decomposers providing ecological services (Naseer *et al.*, 2024). Enhanced biodiversity creates functional redundancy where multiple species perform similar roles, providing ecosystem stability and resilience against environmental perturbations and pest outbreaks (Obiero *et al.*, 2024).

2.3 Greenhouse Gas Mitigation and Environmental Benefits

Rice paddies contribute approximately 10-30% of global agricultural greenhouse gas emissions through methane production in anaerobic waterlogged soils (Naseer *et al.*, 2024; Gupta *et al.*, 2021). Fish

integration reduces methane emissions through multiple interacting mechanisms (Naseer *et al.*, 2024). Fish movements enhance water circulation and oxygen transfer to surface soils, creating aerobic conditions that inhibit methanogenic archaea while supporting methane-oxidizing bacteria populations (Gupta *et al.*, 2021).

Field measurements demonstrate methane emission reductions of 20-64% compared to conventional rice monoculture, representing substantial climate change mitigation benefits (Naseer *et al.*, 2024). Indian rice fields show emission ranges from 2.7 to 6.4 Tg CH₄ year⁻¹, with integrated systems at the lower end (Gupta *et al.*, 2021). Biological weed control by fish reduces weed biomass accumulation that would otherwise decompose anaerobically producing additional methane (Naseer *et al.*, 2024).

Substantial reductions in synthetic nitrogen fertilizer use (20-50%) and pesticide applications (50-90%) eliminate greenhouse gas emissions from agrochemical production, transportation, and field application (Naseer *et al.*, 2024; Obiero *et al.*, 2024). Nitrogen fertilizer production accounts for approximately 2% of global natural gas consumption with substantial carbon dioxide emissions (Gupta *et al.*, 2021). Reduced fertilizer application decreases nitrous oxide emissions from soils, important because nitrous oxide has 298 times the global warming potential of carbon dioxide over 100 years (Gupta *et al.*, 2021).

Comprehensive life cycle assessment studies indicate rice-fish systems achieve 15-40% reductions in total greenhouse gas emissions per kilogram of food output compared to conventional rice monoculture plus separate pond-based aquaculture (Naseer *et al.*, 2024). These emission reductions qualify rice-fish systems for carbon credit generation under emerging agricultural carbon markets, potentially providing additional income streams for adopting farmers (Obiero *et al.*, 2024).

TABLE 1: Comparative Performance Indicators for Rice-Fish Systems versus Rice Monoculture.

Performance Indicator	Rice Monoculture	Rice-Fish Integration	Percent Change	Reference
Land Equivalent Ratio	1.00 (baseline)	1.10 - 1.64	+10% to +64%	Obiero <i>et al.</i> , 2024
Rice grain yield (t/ha)	4.0 - 6.0	3.8 - 6.6	-5% to +15%	Naseer <i>et al.</i> , 2024
Fish production (kg/ha)	0	150 - 3,000	New output	Obiero <i>et al.</i> , 2024
Farmer net income increase	Baseline	+20% to +85%	+20% to +85%	Gul <i>et al.</i> , 2024
Synthetic N fertilizer use	100% (baseline)	50% - 80%	-20% to -50%	Naseer <i>et al.</i> , 2024
Pesticide application	100% (baseline)	10% - 50%	-50% to -90%	Obiero <i>et al.</i> , 2024

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Performance Indicator	Rice Monoculture	Rice-Fish Integration	Percent Change	Reference
Methane emission	100% (baseline)	36% - 80%	-20% to -64%	Naseer <i>et al.</i> , 2024
Water productivity (kg output/m ³)	Baseline	+60% to +130%	+60% to +130%	Naseer <i>et al.</i> , 2024

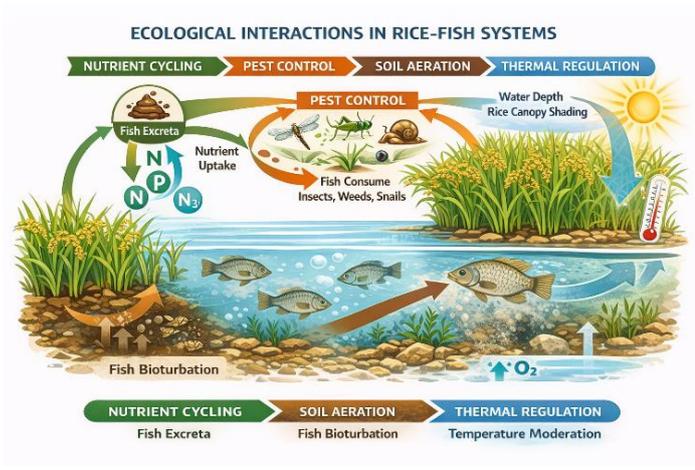


FIGURE 2: Ecological interactions diagram for rice-fish systems showing nutrient cycling pathways with arrows indicating nitrogen flow from fish excreta to rice uptake; pest control services with fish consuming insects, weeds, and snails; soil aeration from fish bioturbation; and thermal regulation through water depth and rice canopy shading.

3.0 SUSTAINABLE AQUACULTURE PRACTICES AND INNOVATIONS

3.1 Microbiome Modulation for Enhanced Fish Health

The fish gut microbiome plays critical regulatory roles in nutrient digestion, immune system function, and disease resistance capacity (Naseer *et al.*, 2024). Modern rice-fish systems increasingly incorporate strategic microbiome management to enhance fish health and productivity, particularly under climate stress conditions compromising immune function (Naseer *et al.*, 2024).

Probiotics, defined as beneficial live microorganisms conferring health benefits when administered adequately, improve fish growth performance, feed utilization efficiency, immune responses, and disease resistance through feed incorporation or water application (Naseer *et al.*, 2024). Common probiotic bacterial strains include *Lactobacillus*, *Bacillus*, and *Saccharomyces* species.

Research demonstrates dietary probiotic supplementation increases fish growth rates by 10-25%, improves feed conversion efficiency by 5-15%, enhances immune parameters including lysozyme

activity and antibody production, and reduces disease susceptibility by 30-60% when challenged with bacterial or viral pathogens (Naseer *et al.*, 2024).

Prebiotics are non-digestible feed ingredients selectively promoting beneficial gut microbiota growth and activity (Naseer *et al.*, 2024). Important prebiotic compounds include beta-glucans, mannan-oligosaccharides, and fructo-oligosaccharides. Rice bran, abundantly available in rice-producing regions, contains significant prebiotic components making it an excellent locally-sourced feed ingredient (Naseer *et al.*, 2024).

Synbiotics combine probiotics and prebiotics in single formulations providing synergistic benefits exceeding either component alone (Naseer *et al.*, 2024). Research shows synbiotic supplementation enhances fish growth by 15-30%, improves disease resistance by 40-70%, and increases stress tolerance under challenging environmental conditions including temperature fluctuations and suboptimal water quality (Naseer *et al.*, 2024).

Biofloc technology cultivates dense populations of beneficial heterotrophic bacteria and microorganisms forming suspended microbial aggregates serving multiple functions (Naseer *et al.*, 2024). These communities convert toxic ammonia into microbial biomass protein that fish consume as supplemental nutrition while improving water quality through nutrient assimilation. Rice-fish systems incorporating biofloc management principles show fish growth improvements of 15-35%, supplemental feed requirement reductions of 20-40%, enhanced water quality parameters, and improved disease resistance (Naseer *et al.*, 2024).

3.2 Immunomodulatory Approaches for Disease Prevention

Immunomodulation encompasses strategies enhancing fish immune system function through dietary supplementation or environmental manipulation, critical for disease control in climate-stressed systems where pathogen pressure increases while host immunity becomes compromised (Naseer *et al.*, 2024).

Plant-derived immunostimulants offer sustainable and cost-effective alternatives to antibiotics for enhancing fish disease resistance (Naseer *et al.*, 2024). Medicinal herbs commonly utilized in Asian aquaculture include garlic (*Allium sativum*), ginger (*Zingiber officinale*), turmeric (*Curcuma longa*), neem (*Azadirachta indica*), and moringa (*Moringa oleifera*). These botanical immunostimulants contain diverse bioactive compounds including phenolics, alkaloids, terpenoids, and saponins that enhance non-specific immune responses, improve antioxidant defense capacity, modulate immune-related gene expression, and exhibit direct antimicrobial properties (Naseer *et al.*, 2024).

Research evidence shows herbal immunostimulant supplementation improves fish disease resistance by 20-45%, enhances growth performance by 15-30%, and increases survival rates by 30-60% when fish face pathogen challenge or environmental stress (Naseer *et al.*, 2024). Many medicinal herbs are locally available in agricultural regions of Africa and Asia, making them economically accessible for smallholder farmers (Naseer *et al.*, 2024).

Beta-glucans are complex polysaccharides derived from yeast cell walls, algae, or cereal grains functioning as potent immunostimulants by activating innate immune responses through pattern

recognition receptors (Naseer *et al.*, 2024). Dietary beta-glucan supplementation at 0.1-2.0% of feed enhances phagocytic activity of macrophages and neutrophils, increases lysozyme and complement activity, stimulates respiratory burst activity, and improves disease resistance against bacterial and viral pathogens (Naseer *et al.*, 2024). Rice bran naturally contains beta-glucans, providing additional immunomodulatory benefits when utilized as dietary ingredient in rice-fish systems (Naseer *et al.*, 2024).

Essential vitamins including vitamin C and E, along with trace minerals such as selenium and zinc, support normal immune function and enhance stress tolerance (Naseer *et al.*, 2024). Vitamin C supplementation at 100-500 mg per kg feed enhances resistance to infectious diseases, improves wound healing, and increases tolerance to environmental stressors (Naseer *et al.*, 2024).

3.3 Precision Nutrition and Local Feed Resources

Optimizing fish nutrition in rice-fish systems enhances productivity, improves health, and promotes environmental sustainability through reduced commercial feed dependency (Gul *et al.*, 2024). Rice-fish systems benefit substantially from utilizing agricultural byproducts and locally available feed resources abundant in rice-producing regions (Naseer *et al.*, 2024).

Rice bran, the outer layer removed during milling, contains 12-15% crude protein and serves as excellent source of lipids, vitamins, minerals, and dietary fiber (Naseer *et al.*, 2024). Optimal dietary inclusion levels range from 15-40% depending on fish species, life stage, and complementary protein source availability (Naseer *et al.*, 2024). Broken rice grains provide high energy supplementing fish dietary requirements, while agricultural crop residues including vegetable wastes, legume byproducts, and oilseed cakes provide additional protein and nutrients (Naseer *et al.*, 2024).

Utilizing locally available feed resources reduces feed costs typically representing 50-70% of total aquaculture production expenses, substantially lowers carbon footprints from commercial feed transportation, and promotes circular economy principles by converting agricultural wastes into valuable fish protein (Gul *et al.*, 2024; Naseer *et al.*, 2024).

While extensive rice-fish systems rely primarily on natural aquatic productivity including algae, zooplankton, benthic invertebrates, and insects, semi-intensive and intensive systems incorporate supplemental feeding to increase fish biomass yields (Naseer *et al.*, 2024). Optimal supplemental feeding rates typically range from 2-5% of total fish body weight per day, with precise rates determined by fish size, water temperature, and natural food organism availability (Naseer *et al.*, 2024; Obiero *et al.*, 2024).

Precision feeding strategies based on careful observation of fish feeding behavior, regular water quality monitoring, and growth performance tracking optimize feed conversion efficiency, minimize nutrient waste degrading water quality, and maintain economic profitability (Naseer *et al.*, 2024).

TABLE 2: Sustainable Aquaculture Innovations for Rice-Fish Systems.

CLIMATE SMART ACTIONS (CSA) AQUACULTURE, AGROFORESTRY AND RESOURCES MANAGEMENT-- ISBN 978-978-60709-1-6

CLIMATE SMART ACTIONS (CSA) AQUACULTURE, AGROFORESTRY AND RESOURCES MANAGEMENT(GLOBAL ISSUES & LOCAL PERSPECTIVES)

Innovation Category	Specific Application	Key Benefits	Implementation Approach	Reference
Probiotics	<i>Lactobacillus</i> , <i>Bacillus</i> , <i>Saccharomyces</i> supplementation	+10-25% growth; +30-60% disease resistance	10 ⁶ -10 ⁸ CFU/g feed or water application	Naseer <i>et al.</i> , 2024
Prebiotics	Beta-glucans, MOS, FOS in diet	Enhanced beneficial gut microbiota; +5-15% growth	0.1-2% dietary inclusion; continuous feeding	Naseer <i>et al.</i> , 2024
Synbiotics	Combined probiotic prebiotic	Synergistic benefits; +15-30% growth; +40-70% disease resistance	Combined application protocols	Naseer <i>et al.</i> , 2024
Herbal immunostimulants	Garlic, ginger, turmeric, neem	+20-45% disease resistance; +15-30% growth	1-5% dietary or water inclusion treatment	Naseer <i>et al.</i> , 2024
Biofloc technology	C:N ratio manipulation; microbial community management	+15-35% growth; 20-40% feed costs; improved water quality	- C:N ratio 10-15:1; carbohydrate supplementation	Naseer <i>et al.</i> , 2024
Vitamin supplementation	Vitamin C, Vitamin E enrichment	Enhanced stress tolerance; improved immune function	100-500 mg/kg feed	Naseer <i>et al.</i> , 2024
Local resources	feed Rice bran, broken rice, agricultural byproducts	Cost reduction; circular economy; reduced carbon footprint	15-40% dietary inclusion	Naseer <i>et al.</i> , 2024

4.0 ENVIRONMENTAL STRESS MANAGEMENT AND BREEDING INNOVATIONS

4.1 Temperature Stress Management Strategies

Climate change increases frequency and intensity of temperature extreme events affecting aquatic systems (Naseer *et al.*, 2024). Rice-fish systems incorporate multiple synergistic strategies for temperature stress mitigation protecting both components.

Maintaining deeper water levels (15-25 cm versus 5-10 cm in conventional paddies) provides significant thermal buffering moderating diurnal and seasonal temperature fluctuations (Naseer *et al.*, 2024). This thermal mass effect reduces maximum temperatures during hot periods and maintains warmer temperatures during cool periods, protecting rice from temperature-induced developmental abnormalities and fish from thermal stress mortality (Naseer *et al.*, 2024; Obiero *et al.*, 2024).

Strategic management of rice canopy density and architecture provides beneficial shade reducing direct solar heating of water surfaces during extreme heat while allowing sufficient light penetration for photosynthesis by rice plants and aquatic primary producers (Naseer *et al.*, 2024). Fish species selection is critically important, prioritizing thermally tolerant species or locally adapted strains surviving and growing across temperature ranges experienced in specific agroecological zones.

Nile tilapia (*Oreochromis niloticus*) tolerates temperatures from 15-42°C with optimal growth at 27-30°C, common carp (*Cyprinus carpio*) tolerates 5-38°C, and certain indigenous African fish species including various cichlids and catfishes show broad thermal tolerance ranges (Naseer *et al.*, 2024). Emergency aeration interventions during extreme heat waves can increase dissolved oxygen concentrations when elevated temperatures simultaneously increase fish metabolic oxygen demand while reducing oxygen saturation capacity (Naseer *et al.*, 2024).

4.2 Water Quality Optimization

Dissolved oxygen is the most critical water quality parameter affecting fish survival and growth (Naseer *et al.*, 2024). Species selection prioritizing air-breathing species like African catfish utilizing atmospheric oxygen or species with high hypoxia tolerance like tilapia and carp provides resilience under oxygen stress conditions (Naseer *et al.*, 2024).

Maintaining appropriate fish stocking densities relative to system carrying capacity prevents oxygen demand from exceeding oxygen supply rates (Naseer *et al.*, 2024). Traditional extensive systems typically stock 500-2,000 fish per hectare while intensive systems may reach 5,000-10,000 fish per hectare with supplemental management interventions including aeration (Naseer *et al.*, 2024; Obiero *et al.*, 2024).

Promoting beneficial algal communities through judicious fertilization provides substantial oxygen production during daylight hours through photosynthesis, though careful management is required to prevent early morning hypoxia when algae and fish respiration consume oxygen without photosynthetic replacement (Naseer *et al.*, 2024). Mechanical aeration using paddle wheels, air diffusers, or splash

aeration during critical periods maintains adequate oxygen levels, though these technologies require energy inputs (Naseer *et al.*, 2024).

Maintaining optimal pH ranges of 6.5-8.5 through limestone application in acidic waters supports fish physiological function and nutrient availability (Naseer *et al.*, 2024). Ammonia control is achieved through multiple pathways including nitrification by autotrophic bacteria, direct plant uptake by rice roots, and in intensive systems through biofloc-mediated heterotrophic bacterial assimilation (Naseer *et al.*, 2024). Maintaining unionized ammonia concentrations below 0.5 mg L⁻¹ prevents ammonia toxicity causing gill damage, growth reduction, and immunosuppression (Naseer *et al.*, 2024).

4.3 Breeding for Climate Resilience

Modern plant breeding programs increasingly target traits supporting rice-fish integration and enhancing climate resilience (Obiero *et al.*, 2024). The SUB1 gene confers tolerance to complete submergence lasting 10-14 days, critically important for rice-fish areas prone to seasonal flooding (Naseer *et al.*, 2024). Submergence-tolerant rice varieties maintain grain yields even after prolonged flooding events killing conventional varieties (Naseer *et al.*, 2024; Obiero *et al.*, 2024).

Drought-tolerant rice varieties incorporating quantitative trait loci for drought resistance provide flexibility for implementing water-saving practices during water scarcity periods (Naseer *et al.*, 2024). Traditional deepwater rice varieties rapidly elongating during flooding to maintain photosynthetic leaf tissues above water level suit rice-fish systems in deeply flooded environments (Naseer *et al.*, 2024).

Incorporating genetic resistance to major rice pests and diseases including bacterial blight, blast disease, and brown planthopper reduces pest pressure even with fish biological control, creating more robust integrated systems (Naseer *et al.*, 2024). Rice varieties with enhanced nitrogen use efficiency reduce synthetic fertilizer requirements while maintaining productivity, synergizing with biological nitrogen fertilization from fish excreta (Naseer *et al.*, 2024; Obiero *et al.*, 2024).

Fish genetic improvement through selective breeding enhances traits supporting rice-fish system productivity and climate resilience (Naseer *et al.*, 2024). Selective breeding programs targeting growth rate, feed conversion efficiency, and favorable body conformation increase system productivity and economic returns. Genetically improved tilapia strains demonstrate 10-15% faster growth than unimproved foundation stocks under diverse environmental conditions (Naseer *et al.*, 2024; Obiero *et al.*, 2024).

Selecting fish strains with enhanced thermal tolerance enables culture across wider temperature ranges, improving climate resilience (Naseer *et al.*, 2024). Selective breeding for disease resistance, particularly against economically important bacterial and viral pathogens, reduces mortality rates and improves system stability (Naseer *et al.*, 2024).

Many African freshwater fish species possess desirable traits for rice-fish culture yet remain underutilized in modern aquaculture (Gul *et al.*, 2024). African catfish (*Clarias gariepinus*) is air-breathing enabling survival under low oxygen conditions, demonstrates omnivorous feeding behavior reducing supplemental feed requirements, exhibits rapid growth reaching one kilogram in 6-8 months,

and commands high market values in Nigerian markets (Gul *et al.*, 2024). Multiple tilapia species native to Africa including Nile tilapia, blue tilapia, and Mozambique tilapia possess desirable traits including omnivorous feeding, broad temperature tolerance, rapid growth rates, and consumer acceptance (Gul *et al.*, 2024; Obiero *et al.*, 2024).

Developing appropriate aquaculture technologies for indigenous African fish species offers multiple advantages including genetic adaptation to local environmental conditions, cultural dietary preferences, and potential resistance to endemic diseases compared to exotic introduced species (Gul *et al.*, 2024; Obiero *et al.*, 2024).

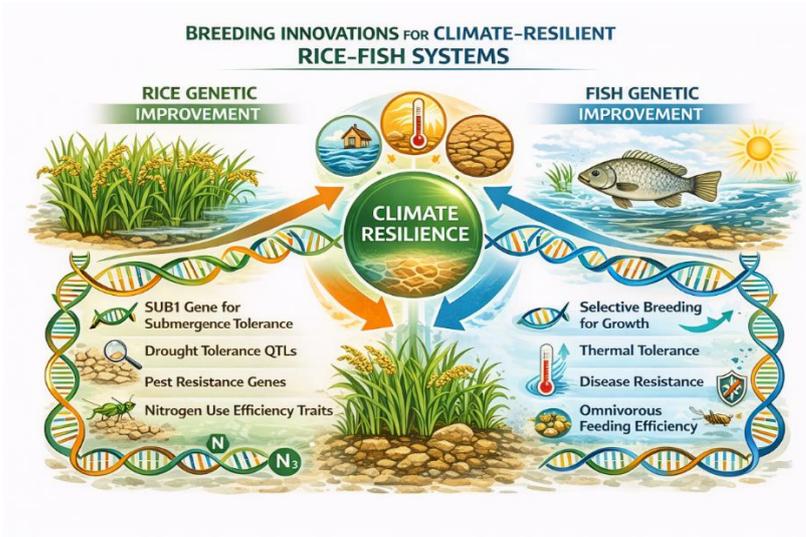


FIGURE 3: Breeding innovations diagram showing parallel tracks for rice and fish genetic improvement. For rice: show SUB1 gene for submergence tolerance, drought tolerance QTLs, pest resistance genes, and nitrogen use efficiency traits. For fish: show selective breeding for growth, thermal tolerance, disease resistance, and omnivorous feeding efficiency.

5.0 DISEASE CONTROL AND RENEWABLE ENERGY INTEGRATION

5.1 Integrated Disease Management Strategies

Climate change intensifies disease risks in aquaculture through accelerated pathogen proliferation rates and host immunosuppression under environmental stress conditions (Naseer *et al.*, 2024). Integrated disease management in rice-fish systems combines preventive biosecurity measures, diagnostic surveillance, and control strategies.

Biosecurity protocols including quarantine procedures for new fish introductions, sourcing certified disease-free fingerlings from reputable hatcheries, equipment disinfection protocols, movement restrictions during disease outbreaks, and visitor controls prevent pathogen introduction into production systems (Naseer *et al.*, 2024). Regular health monitoring through visual observation of fish behavior and appearance, combined with periodic diagnostic testing, enables early disease detection allowing timely intervention before significant mortality occurs (Naseer *et al.*, 2024).

Controlling intermediate hosts and disease vectors through biological control mechanisms reduces disease transmission pathways (Naseer *et al.*, 2024). Fish consumption of snails and copepods serving as intermediate hosts for parasitic diseases provides natural disease suppression. Competitive exclusion through establishment of beneficial microbiota prevents pathogen colonization of fish mucosal surfaces, with research demonstrating 30-60% reductions in disease incidence with strategic probiotic administration (Naseer *et al.*, 2024).

Maintaining optimal environmental conditions, avoiding overcrowding stress, implementing gentle handling procedures during harvesting and sorting, and ensuring nutritional adequacy support fish immune system function preventing opportunistic infections (Naseer *et al.*, 2024). When antimicrobial therapeutics are necessary, judicious use following definitive diagnostic confirmation, administration of appropriate dosages for recommended treatment durations, and observance of withdrawal periods before harvest prevents antimicrobial resistance development and ensures food safety (Naseer *et al.*, 2024).

Although currently limited commercial vaccines exist for food fish species, ongoing advancements in vaccine development technologies including DNA vaccines, oral vaccine delivery systems, and immersion vaccination protocols show promise for protecting against major bacterial and viral pathogens (Naseer *et al.*, 2024).

5.2 Renewable Energy Applications

Energy requirements in rice-fish production systems include water pumping for irrigation and circulation, aeration during critical low-oxygen periods, post-harvest processing operations, and product transportation (Naseer *et al.*, 2024). Renewable energy integration enhances environmental sustainability and reduces operational costs while improving climate change mitigation.

Solar photovoltaic panels powering electric water pumps provide reliable, low-cost irrigation water supply without dependence on electrical grid infrastructure or diesel fuel combustion (Naseer *et al.*, 2024). This technology is particularly valuable in off-grid rural areas where rice-fish systems predominantly occur and where grid electricity is either unavailable or unreliable (Naseer *et al.*, 2024).

Solar-powered aeration systems using paddle wheels or air diffusers maintain adequate dissolved oxygen concentrations during critical periods including early morning hours and extreme heat events (Naseer *et al.*, 2024). These systems operate autonomously using stored solar energy, reducing mortality risks during hypoxic events without requiring fossil fuel inputs (Naseer *et al.*, 2024).

Solar drying technologies for fish and rice post-harvest processing reduce product losses, improve quality characteristics, and eliminate firewood consumption with associated deforestation and greenhouse gas emissions (Naseer *et al.*, 2024). Solar-powered lighting enables night operations and monitoring activities, while solar-powered sensors and monitoring systems enable precision management without grid connectivity requirements (Naseer *et al.*, 2024).

Anaerobic digestion systems processing agricultural waste materials including rice straw, rice husks, and fish processing byproducts produce biogas fuel for cooking and space heating applications (Naseer

et al., 2024). This technology closes nutrient cycles while generating renewable energy, with digestate effluent providing nutrient-rich organic fertilizer applicable to rice fields completing circular economy principles (Naseer *et al.*, 2024).

In landscapes with elevation gradients, micro-hydropower systems utilizing gravitational water flow from elevated storage reservoirs to lower paddy fields can generate electricity for system operations (Naseer *et al.*, 2024). Although site-specific and requiring appropriate topography, this approach provides continuous renewable power generation where feasible.

Gravity-driven water distribution systems utilizing elevated water storage to provide pressure for distribution throughout paddies reduce pumping energy requirements substantially (Naseer *et al.*, 2024). Using energy-efficient equipment including high-efficiency pumps, low-power aerators, and efficient processing machinery reduces total electricity consumption per unit production output (Naseer *et al.*, 2024). Timing energy-intensive operations to coincide with periods of peak solar energy generation maximizes renewable energy utilization and minimizes grid electricity or fossil fuel requirements (Naseer *et al.*, 2024).

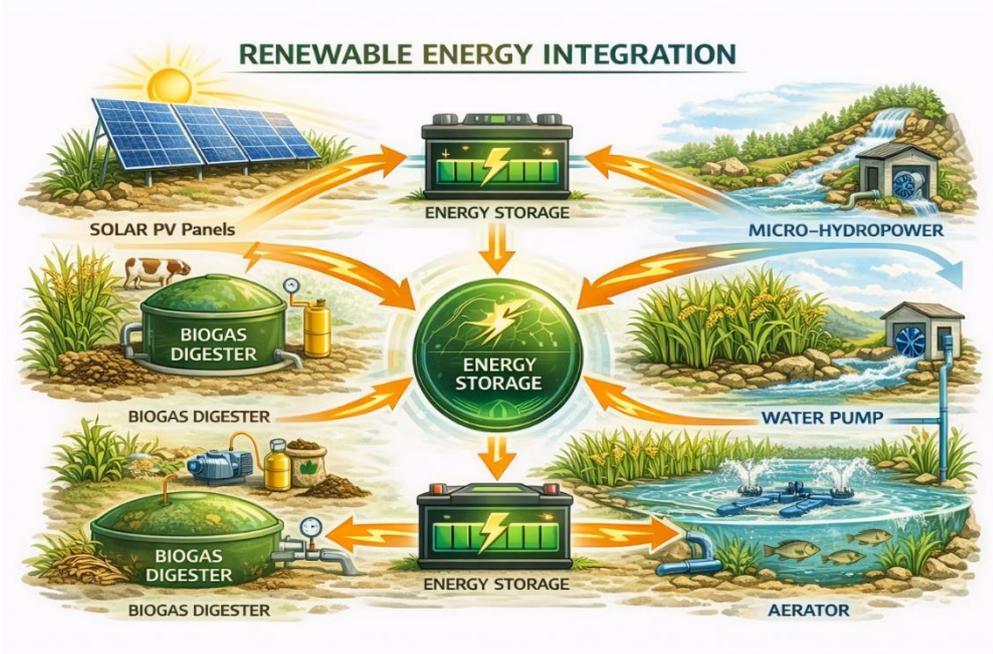


FIGURE 4: Renewable energy integration schematic showing solar photovoltaic panels connected to water pumps and aerators, biogas digester system processing agricultural waste and producing cooking fuel and organic fertilizer, micro-hydropower from elevation gradient, and energy flow arrows connecting all components.

6.0 CASE STUDIES AND ADAPTATION OPPORTUNITIES

6.1 Asian Model Systems

China - Qingtian Rice-Fish System: The Qingtian rice-fish system in Zhejiang Province, designated as Globally Important Agricultural Heritage System, demonstrates long-term sustainability spanning centuries of continuous practice (Obiero *et al.*, 2024). This system cultivates common carp (*Cyprinus carpio*) within paddy rice fields using semi-intensive management. Fish are stocked at densities of 2,500-4,000 individuals per hectare with minimal supplemental feeding relying primarily on natural productivity, and organic fertilization provides nutrients supporting both rice and aquatic food webs (Obiero *et al.*, 2024).

Rice grain yields range from 4.5 to 6.0 tonnes per hectare while fish production ranges from 300 to 600 kg per hectare, achieving Land Equivalent Ratios of 1.25 to 1.40 indicating 25-40% higher productivity than separate monocultures (Obiero *et al.*, 2024). Environmental benefits include 45% reduction in chemical fertilizer requirements, 65% reduction in pesticide applications, and substantially enhanced biodiversity compared to conventional monoculture (Obiero *et al.*, 2024). Economic analysis demonstrates 35-55% higher net income for rice-fish farmers compared to rice monoculture farmers (Obiero *et al.*, 2024).

Bangladesh - Community-Based Rice-Fish Systems: Bangladesh pioneered rice-fish integration in seasonally flooded lowland areas specifically addressing food security and poverty alleviation objectives (Obiero *et al.*, 2024). Systems utilize mixed culture of indigenous small fish species including mola (*Amblypharyngodon mola*), punti (*Puntius* species), and small prawns in deepwater rice varieties. Management is extensive with natural fish recruitment or very low-density stocking, no supplemental feeding relying entirely on natural productivity, and submergence-tolerant rice varieties enabling survival during flooding (Obiero *et al.*, 2024).

Rice yields range from 2.5 to 3.5 tonnes per hectare while fish production ranges from 150 to 400 kg per hectare (Obiero *et al.*, 2024). Nutritional benefits are substantial with fish retained for direct household consumption providing essential micronutrients including vitamin A, iron, and zinc addressing hidden hunger and malnutrition, particularly benefiting women and children most vulnerable to micronutrient deficiencies (Obiero *et al.*, 2024; Hwalla *et al.*, 2016).

Social impact studies document women's economic empowerment through participation in fish processing and local marketing activities, 30-40% reduction in household income variability providing economic stability, and improved food security during lean seasons when rice stocks are depleted but fish remain available (Obiero *et al.*, 2024).

Myanmar - Experimental Rice-Fish Trials: Recent trials in Myanmar's Ayeyarwady Delta demonstrated that rice-fish integration maintained rice productivity at 4.85 Mg ha⁻¹ (equivalent to monoculture) while producing 700-940 kg ha⁻¹ fish using only 13% of field area for fish refuge (Dubois *et al.*, 2019). Compared to rice monoculture under best management practices, integrated systems improved gross profit margins by 9-41% across two locations (Dubois *et al.*, 2019). Approximately 70% of fish produced was sold to local markets purchased by rural and peri-urban consumers, while 30% was consumed by farming households, indicating potential to improve both market supply and household nutrition (Dubois *et al.*, 2019).

6.2 Nigerian Adaptation Potential and Strategies

Favorable Conditions: Nigeria possesses multiple favorable conditions for rice-fish system adoption and scaling (Gul *et al.*, 2024). These include expanding rice cultivation area currently at 3.7 million hectares with government targets for further expansion, growing aquaculture sector producing 380,000 tonnes annually, diverse agroecological zones spanning humid tropical rainforest to semi-arid Sahel enabling varied system designs, strong policy support for agricultural diversification and food security, and large domestic markets for both rice and fish with growing middle-class demand for protein (Gul *et al.*, 2024).

Significant Challenges: However, significant challenges constrain widespread adoption. Predominance of rainfed production systems accounting for 70% of rice cultivation with limited water control infrastructure complicates fish integration requiring stable water depth (Gul *et al.*, 2024). Minimal extension service knowledge and training materials on rice-fish integration limits farmer awareness and technical capacity. Limited availability of improved fish fingerlings from quality hatcheries constrains production potential. Infrastructure deficiencies including poor rural road networks, limited cold chain facilities, and inadequate processing infrastructure increase post-harvest losses and reduce market access. Fragmented smallholder land holdings averaging 1-3 hectares per household may limit economies of scale though cooperatives can address this constraint (Gul *et al.*, 2024; Chidiebere-Mark *et al.*, 2019).

Energy analysis reveals rice production in Nigeria consumes 14,000-15,000 MJ ha⁻¹ with chemical energy from fertilizers contributing 73-77% of total input, thermal energy 10.5-12.3%, mechanical energy 3.9-6.4%, and manual energy only 2.2-2.3%, indicating very low mechanization levels (Kosemani and Bamgboye, 2020). Labour constitutes 72-76% of total production costs across different systems, with swamp systems showing highest profitability (29.37% return), followed by lowland (20.10%) and upland (13.03%) systems (Chidiebere-Mark *et al.*, 2019).

Strategic Adaptation Approaches: Adaptation approaches should include establishing demonstration plots and research stations across major agroecological zones to showcase productivity gains, economic benefits, and management protocols under local conditions (Gul *et al.*, 2024; Obiero *et al.*, 2024). Species selection must prioritize African catfish (*Clarias gariepinus*) in southern humid regions where it is culturally preferred and well-adapted, Nile tilapia in northern irrigated rice schemes with better water control, and indigenous species where local dietary preferences favor them (Gul *et al.*, 2024).

Technical training programs targeting farmers, extension agents, input suppliers, and market actors should build comprehensive capacity across the value chain (Gul *et al.*, 2024; Obiero *et al.*, 2024). Developing input supply systems including establishing disease-free hatchery networks producing quality fingerlings and creating feed mills utilizing locally available ingredients like rice bran, broken rice, and agricultural byproducts reduces costs and improves sustainability (Gul *et al.*, 2024).

Policy support mechanisms should explicitly integrate rice-fish systems into national agricultural development policies and programs, provide targeted financial incentives and subsidies for pioneer farmers adopting integrated practices, develop quality standards and certification systems for rice-fish products enabling premium marketing, and ensure secure land tenure encouraging long-term investments (Gul *et al.*, 2024; Obiero *et al.*, 2024).

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Value chain development requires establishing fish collection centers and cold storage facilities in major production areas, developing processing infrastructure for value addition, and linking farmers directly to urban premium markets and export opportunities (Gul *et al.*, 2024). Adaptive research programs should conduct location-specific studies on optimal rice varieties, fish species and stocking densities, water management protocols, and integrated pest management approaches using participatory methods engaging farmers in research design and evaluation (Gul *et al.*, 2024; Obiero *et al.*, 2024).

Priority Geographic Regions: Priority regions for initial piloting and scaling include the Niger Delta region favorable for African catfish culture, with documented indigenous rice-fish traditions and flood-prone lowlands benefiting from deepwater rice-fish systems (Gul *et al.*, 2024). Northern Fadama lands and formal irrigation schemes in Kano, Kaduna, and Kebbi States with established water control infrastructure are suitable for intensive rice-fish systems. Southern rainforest and humid Guinea savanna zones with high rainfall and ample water availability support extensive rice-fish systems using tilapia and carp species (Gul *et al.*, 2024).

TABLE 3: Priority Recommendations for Nigerian Rice-Fish System Development.

Strategic Area	Specific Recommendation	Implementation Approach	Expected Outcome	Reference
Demonstration	Establish 10-15 pilot sites across agroecological zones	Partner with NIFFR, universities, and ADPs	Validated state location-specific protocols	Gul <i>et al.</i> , 2024; Obiero <i>et al.</i> , 2024
Species Selection	Prioritize African catfish (south), Nile tilapia (north), indigenous species	Develop certified hatchery network with biosecurity	Reliable quality fingerling supply	Gul <i>et al.</i> , 2024
Training	Train 1,000 farmers and 100 extension agents in first phase	Practical farmer field schools; manuals	Technical competence for adoption	Gul <i>et al.</i> , 2024; Obiero <i>et al.</i> , 2024
Infrastructure	Develop water control in 5 priority irrigation schemes	Public infrastructure investment; sector engagement	Enhanced private system water management	Gul <i>et al.</i> , 2024
Policy	Integrate rice-fish into Federal Agricultural Policy	Inter-ministerial task force; incentive design	Enabling policy environment	Gul <i>et al.</i> , 2024; Obiero <i>et al.</i> , 2024
Research	Conduct adaptive trials on varieties, densities, management	University and NIFFR led participatory research	Location-specific technical packages	Gul <i>et al.</i> , 2024
Value Chain	Establish 20 collection centers with cold storage	Public-private partnerships; cooperative investment	Improved market access and prices	Gul <i>et al.</i> , 2024

Note: NIFFR = National Institute for Freshwater Fisheries Research; ADP = Agricultural Development Programme.



FIGURE 5: Map of Nigeria showing agroecological zones (rainforest, derived savanna, Guinea savanna, Sudan savanna, Sahel), existing major rice production areas marked with rice symbols, aquaculture production concentrations marked with fish symbols, and priority regions for rice-fish system development highlighted with different colors/patterns.

7.0 CONCLUSION

Rice-fish farming systems represent powerful climate-smart agricultural solutions simultaneously addressing interconnected global challenges of food security, climate change adaptation, and environmental sustainability. Comprehensive evidence from diverse geographical contexts demonstrates integration achieves 10-64% productivity gains through beneficial ecological synergies, with systems producing substantially more output per unit land area than separate monocultures (Obiero *et al.*, 2024; Dubois *et al.*, 2019). These productivity enhancements arise from ecological mechanisms including biological nitrogen fertilization from fish excreta reducing synthetic fertilizer requirements by 20-50%, comprehensive biological pest control enabling 50-90% pesticide reductions, soil aeration from fish bioturbation activities, and thermal buffering from deeper water depths (Naseer *et al.*, 2024; Obiero *et al.*, 2024).

Rice-fish systems enhance climate adaptation through risk diversification across production pathways with differential environmental sensitivities, thermal regulation protecting both rice and fish from temperature extremes through 2-4°C water temperature reductions during heat waves, enhanced water

productivity improving efficiency by 60-130%, and ecosystem biodiversity supporting 2-3 times more beneficial organism species providing functional redundancy and stability (Naseer *et al.*, 2024; Obiero *et al.*, 2024).

Climate change mitigation benefits include substantial greenhouse gas emission reductions of 20-64% for methane through enhanced soil oxygenation, decreased agrochemical production and application emissions through 20-50% synthetic fertilizer reduction and 50-90% pesticide reduction, and improved overall carbon footprint per unit food output achieving 15-40% reductions compared to conventional systems (Naseer *et al.*, 2024; Gupta *et al.*, 2021).

Modern innovations enhance transformative potential across multiple technological domains (Naseer *et al.*, 2024). Microbiome modulation strategies including probiotic, prebiotic, and synbiotic supplementation improve fish growth by 10-30% and disease resistance by 30-70%. Immunomodulatory approaches utilizing herbal immunostimulants and beta-glucans enhance immune function and stress tolerance under climate variability. Breeding innovations developing submergence-tolerant and drought-tolerant rice varieties combined with thermally tolerant and disease-resistant fish strains create more resilient integrated systems. Integrated disease management combining biosecurity, probiotics, and judicious therapeutic interventions maintains fish health. Renewable energy integration utilizing solar photovoltaic, biogas, and micro-hydropower technologies reduces fossil fuel dependency and operational costs (Naseer *et al.*, 2024; Obiero *et al.*, 2024).

For Nigeria, rice-fish integration presents compelling opportunities to simultaneously enhance rice productivity addressing the nation's import dependency and production gap, develop sustainable aquaculture increasing domestic fish production currently at 380,000 tonnes, improve rural livelihoods through diversified income streams with 20-85% income increases, and address nutritional insecurity through increased availability of protein and essential micronutrients (Gul *et al.*, 2024; Dubois *et al.*, 2019; Hwalla *et al.*, 2016). Despite current constraints including limited technical capacity, inadequate infrastructure, and fragmented policy frameworks, Nigeria possesses favorable foundational conditions including 3.7 million hectares of rice cultivation with expansion potential, diverse agroecological zones enabling varied system designs, established aquaculture sector providing technical foundation, and strong policy commitment to agricultural transformation and food security (Gul *et al.*, 2024).

Realizing transformative potential across Nigeria requires coordinated multi-stakeholder action across several strategic fronts (Gul *et al.*, 2024; Obiero *et al.*, 2024). Policy integration must develop frameworks explicitly recognizing and incentivizing rice-fish adoption within national agricultural development programs and climate change adaptation strategies. Capacity building should systematically train farmers, extension agents, input suppliers, and value chain actors in integrated system design, management, and marketing. Input supply system development must establish certified disease-free hatchery networks and local feed manufacturing utilizing agricultural byproducts. Infrastructure investment should prioritize water control structures in key rice-growing regions, rural road networks improving market access, and cold chain facilities reducing post-harvest losses currently estimated at 30-40%. Adaptive research programs should conduct location-specific participatory trials validating optimal varieties, species, stocking densities, and management protocols. Value chain development should establish collection centers, develop quality standards enabling premium marketing, and forge direct market linkages. Climate finance mobilization should access Green Climate

Fund resources, develop carbon credit programs for verified emission reductions achieving 15-40% reductions in greenhouse gas emissions per kilogram food output, and attract impact investment capital. Knowledge sharing should document indigenous practices, create communities of practice connecting farmers, and develop culturally appropriate extension materials in local languages.

Rice-fish systems embody fundamental ecological principles underlying truly sustainable agriculture including functional diversity creating complementary resource use, closed-loop integration minimizing external inputs and waste, enhanced efficiency producing more output from same resources, and ecosystem resilience providing stability under environmental perturbations (Naseer *et al.*, 2024; Obiero *et al.*, 2024). As climate change accelerates and food security challenges intensify across Nigeria and globally, these ancient practices enhanced with modern scientific innovations offer proven pathways toward productive, resilient, and environmentally responsible food production systems. The imperative now lies in strategically scaling these solutions through coordinated research, policy, and development investments while thoughtfully adapting approaches to diverse local contexts, maintaining the ecological integrity that fundamentally enables long-term sustainability.

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