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Water quality as a driver of aquatic biodiversity in integrated rice-fish culture systems in Ebonyi State, Nigeria

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ABSTRACT: Integrated rice–fish farming is a sustainable production system that enhances food production while supporting freshwater biodiversity. This study evaluated the influence of water quality on aquatic biodiversity in integrated rice–fish culture systems in Ebonyi State, Nigeria. Field experiments were conducted from June 2022 to December 2023 in Ezza North, Onicha and Afikpo South Local Government Areas using integrated rice–fish (RF) and rice monoculture (RM) systems. *Clarias gariepinus* juveniles were stocked at 0.4 fish m^{-2} in refuge trenches. Physicochemical parameters, phytoplankton, zooplankton, aquatic macrophytes and benthic macroinvertebrates were assessed using standard methods. Biodiversity was evaluated using the Shannon–Wiener, Margalef, Pielou's evenness and dominance indices, and data were analysed with IBM SPSS Statistics version 22.0. The integrated system supported significantly higher aquatic biodiversity than the conventional system, with improved dissolved oxygen, nutrient availability and habitat complexity. Diversity, richness and evenness indices were significantly higher, whereas dominance was lower in the integrated system. Dissolved oxygen, pH and nutrient concentrations significantly influenced aquatic community composition. The findings demonstrate that integrated rice–fish farming improves water quality, conserves aquatic biodiversity and promotes environmentally sustainable agricultural production in tropical freshwater ecosystems.

Keywords: Aquatic biodiversity, *Clarias gariepinus*, integrated rice–fish farming, Nigeria, water quality.

INTRODUCTION

Rice (*Oryza sativa* L.) is one of the world's most important food crops, providing a major source of dietary energy and livelihood for billions of people. In sub-Saharan Africa, demand for rice has increased substantially over the last two decades owing to rapid population growth, urbanisation, and changing dietary preferences. Nigeria is the largest producer and consumer of rice in West Africa; however, domestic production remains inadequate to satisfy national demand because of declining soil fertility, inefficient water management, pest infestation, biodiversity loss, and the increasing impacts of climate variability. Consequently, improving rice productivity while maintaining environmental sustainability has become a major priority for agricultural development (FAO, 2024b; Ling Ling *et al*., 2024).

Integrated rice–fish farming has emerged as one of the most promising climate-smart agricultural practices for improving food production while conserving ecosystem integrity. The system involves the simultaneous cultivation of rice and fish within the same field, thereby promoting ecological interactions that enhance nutrient cycling, increase resource-use efficiency, diversify farm income, and reduce dependence on synthetic fertilisers and pesticides. Fish activities, including sediment bioturbation, nutrient mineralisation, and natural suppression of insect pests and weeds, improve soil fertility and create favourable environmental conditions for rice growth. In addition, fish excreta serve as organic fertiliser, while fish movement improves water circulation and oxygen availability within flooded rice fields. These ecological processes collectively enhance agricultural productivity and environmental sustainability compared with conventional rice monoculture (Hou *et al*., 2024; Ling Ling *et al*., 2024; Halwart and Gupta, 2004; Sathoria and Roy, 2022; Xie *et al*., 2011).

Rice fields also function as temporary freshwater ecosystems that support diverse biological communities, including phytoplankton, zooplankton, aquatic macrophytes, benthic macroinvertebrates, microorganisms, amphibians, and fish. These organisms play indispensable ecological roles in primary production, nutrient recycling, organic matter decomposition, food-web dynamics, and ecosystem resilience. Phytoplankton constitute the principal primary producers that sustain aquatic food chains, whereas zooplankton serve as important links between primary producers and higher trophic levels. Aquatic macrophytes provide habitat complexity, refuge, and spawning substrates for numerous aquatic organisms, while benthic macroinvertebrates contribute significantly to sediment decomposition and nutrient regeneration. Consequently, the composition and diversity of these aquatic communities are widely recognised as reliable indicators of freshwater ecosystem health.

The structure and productivity of aquatic communities are strongly influenced by physicochemical characteristics of water. Environmental variables such as temperature, pH, dissolved oxygen, transparency, turbidity, electrical conductivity, nutrient concentrations, and organic matter regulate the survival, abundance, distribution, and diversity of aquatic organisms. Improved water quality generally supports greater species richness and ecological stability, whereas poor environmental conditions reduce biodiversity and favour pollution-tolerant taxa. Recent studies have demonstrated that integrated rice–fish farming significantly improves water quality through enhanced nutrient recycling, efficient utilisation of nitrogen and phosphorus, and increased biological interactions, thereby creating a more favourable environment for aquatic biodiversity than conventional rice monoculture (Hou *et al*., 2024).

Recent investigations have further demonstrated that integrated rice–fish farming improves ecosystem services beyond increasing crop and fish yields. By enhancing nutrient cycling and maintaining favourable environmental conditions, integrated systems promote the development of diverse planktonic communities that form the foundation of aquatic food webs. Welde *et al*. (2024) reported significantly greater phytoplankton and microzooplankton diversity in rice–fish production systems than in conventional rice monoculture, attributing these differences to improved nutrient availability and water quality. Likewise, Diao *et al*. (2024) showed that integrating fish into rice fields altered bacterioplankton community composition and strengthened ecological processes involved in nutrient transformation and ecosystem stability. These findings collectively demonstrate that rice–fish integration contributes not only to agricultural productivity but also to improved ecological functioning.

In Nigeria, integrated rice–fish farming is increasingly being promoted as a sustainable approach to strengthening food security and improving rural livelihoods. Between 2021 and 2023, the Food and Agriculture Organisation (FAO), in collaboration with the University of Ibadan and international partners, implemented pilot integrated rice–fish farming projects in Ebonyi and Kebbi States. The project demonstrated that integrating fish into rice fields increased rice yield by approximately 5% while substantially improving farmers' incomes, dietary diversity, and overall household food security. Farmers also reported reduced pest problems and lower dependence on external agricultural inputs, highlighting the environmental and socioeconomic advantages of the production system (FAO, 2024b).

Earlier investigations in Ebonyi State also showed increasing awareness and adoption of integrated rice–fish farming technologies among farmers. Onoh *et al*. (2020) observed that farmers recognised integrated rice–fish farming as a profitable and environmentally friendly production system capable of improving resource utilisation and household income, although adoption remained constrained by limited technical knowledge and inadequate extension support. These findings suggest that while integrated rice–fish farming has considerable potential in southeastern Nigeria, further scientific evidence is required to support its wider adoption and sustainable management. Therefore, the objective of this study is to evaluate the effects of integrated rice–fish culture on water quality, aquatic biodiversity, and biological productivity in rice-based production systems across Ezza North, Onicha, and Afikpo South Local Government Areas of Ebonyi State, Nigeria.

MATERIALS AND METHODS

Study area

The study was conducted in three major rice-producing communities in Ebonyi State, southeastern Nigeria, namely Ezza North, Onicha, and Afikpo South Local Government Areas (Table 1). These locations were selected based on recommendations from the Food and Agriculture Organisation (FAO) because they represent established pilot sites for integrated rice–fish farming in southeastern Nigeria. The sites also possess suitable hydrological conditions, extensive lowland rice fields, and active participation of farming households in integrated rice–fish production.

Ebonyi State lies within the humid tropical rainforest zone of southeastern Nigeria between latitudes 5°40′–6°45′ N and longitudes 7°30′–8°30′ E. The climate is characterised by two distinct seasons comprising the rainy season (April–October) and the dry season (November–March). Mean annual rainfall ranges between approximately 2,000 and 2,200 mm, while average annual

Table 1. Description of the experimental sites.

Study Site	Local Government Area	Production System	Major Ecological Characteristics
Ezza North	Ezza North	Rice–Fish (RF) and Rice Monocropping (RM)	Lowland floodplain, perennial water supply, intensive rice cultivation
Isieke	Onicha	Rice–Fish (RF) and Rice Monocropping (RM)	Freshwater wetland with seasonal flooding and extensive rice fields
Amachi	Afikpo South	Rice–Fish (RF) and Rice Monocropping (RM)	Floodplain ecosystem with natural ponds supporting aquatic biodiversity

temperature varies from 27 to 30°C. Relative humidity generally exceeds 70% during the rainy season, creating favourable environmental conditions for rice cultivation and freshwater biological communities.

The three study locations are situated within lowland floodplain ecosystems characterised by seasonal inundation, clay-loam soils, and abundant freshwater resources. Numerous ponds, streams, and wetlands occurring within the landscape provide natural habitats for diverse aquatic flora and fauna, making the area suitable for evaluating biodiversity responses under integrated rice–fish culture systems.

Participatory Rural Appraisal (PRA)

Prior to field investigations, a Participatory Rural Appraisal (PRA) was undertaken to obtain baseline ecological and socio-environmental information regarding integrated rice–fish farming practices. The PRA followed established participatory methodologies involving reconnaissance surveys, focus group discussions, semi-structured interviews, direct field observations, and consultations with experienced farmers and community leaders. These activities provided valuable indigenous knowledge on the occurrence, utilisation, seasonal abundance, and local identification of aquatic flora and fauna associated with rice–fish farming systems.

Three complementary participatory approaches were employed: Overall situation assessment; Village-level participatory inquiry; and Focused interviews with key informants possessing extensive indigenous ecological knowledge. These participatory methods enhanced field observations by integrating local ecological knowledge with scientific sampling protocols, thereby improving the reliability and ecological relevance of the biodiversity assessment.

Experimental design

The experiment was conducted over an 18-month period from June 2022 to December 2023 to capture both wet and dry season variability. Two production systems were evaluated: (1). Conventional rice monocropping (RM), which served as the control treatment; (2) Integrated rice–fish culture (RF), in which rice and African catfish (*Clarias gariepinus*) were cultured simultaneously.

Each treatment was established at the three study locations using identical field dimensions. Experimental rice fields measured approximately 100 × 50 ft. Refuge trenches measuring approximately 0.9 m in width and 0.9 m in depth were excavated around the perimeter of each rice–fish plot to provide permanent aquatic refuge for stocked fish. Earthen dikes approximately 0.6 m high were constructed to prevent flooding and maintain water levels throughout the production cycle. Water was supplied from adjacent natural ponds using portable pumping machines whenever supplementation was required.

Rice seedlings of the dominant Abakaliki variety were transplanted using recommended agronomic spacing. No inorganic fertilisers, herbicides, or pesticides were applied throughout the experimental period in order to minimise anthropogenic influences on aquatic biodiversity.

Fish stocking and farm management

Thirty days after rice transplantation, juvenile African catfish (*Clarias gariepinus*) were stocked into each integrated rice–fish plot. Fish had a mean total length of 13.19 ± 0.18 cm and a mean body weight of 40.00 ± 5.18 g. Stocking density was maintained at 0.4 fish m^{-2}, corresponding to 1,000 juveniles per experimental plot. Fish were allowed unrestricted movement between refuge trenches and flooded rice fields throughout the production period. Routine management practices, including supplementary feeding, periodic water regulation, weed control, and health monitoring, were carried out uniformly across all integrated culture systems.

Water quality assessment

Water samples were collected bimonthly from three randomly selected sampling points within each experimental field between 08:00 and 10:00 h to minimise diel fluctuations. Samples were preserved at approximately 4°C and transported immediately to the laboratory for physicochemical analyses.

The following physicochemical variables were determined: Dissolved oxygen (DO); Water temperature; pH; Total nitrogen (TN); Ammonia–nitrogen (NH_4^+–N); Nitrate; Phosphate; Electrical conductivity; Total dissolved solids (TDS); Biochemical oxygen demand (BOD); and Chemical oxygen demand (COD)

Dissolved oxygen was measured in situ using a calibrated HQ30D multiparameter meter (HACH, USA), while total nitrogen was determined using the alkaline potassium persulfate digestion method. Ammonia concentration was analysed using the Nessler colourimetric method following standard laboratory procedures (APHA, 2017).

Collection and identification of aquatic organisms

Phytoplankton, zooplankton, aquatic macrophytes, and benthic macroinvertebrates were sampled simultaneously with water quality assessments. Phytoplankton samples were obtained by collecting 1 L composite water samples and preserving them with Lugol's iodine solution. Zooplankton were collected by filtering 20 L of water through a 112-μm plankton net and preserved in 4% formaldehyde. Species identification was undertaken using standard taxonomic keys and freshwater identification manuals.

Benthic macroinvertebrates were collected using a 6-cm diameter corer from six randomly selected sampling points within each paddy field. Samples were sieved through a 200-μm mesh, preserved in 4% formaldehyde, sorted under stereoscopic microscopes, and identified to the lowest practicable taxonomic level using internationally recognised identification guides.

Biodiversity assessment

Community structure was evaluated using standard ecological indices. Relative abundance, Shannon–Wiener diversity index (H′), Margalef species richness index (D), Pielou's evenness index (J′), and dominance index (Y) were calculated for each biological community. The Shannon–Wiener, Margalef and Pielou indices were applied following Shannon and Weaver (1949), Margalef (1958), and Pielou (1966), respectively. Species with dominance values greater than 0.02 were regarded as dominant taxa.

Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics version 22.0. Descriptive statistics were calculated as means ± standard deviations. Differences between integrated rice–fish culture and rice monocropping systems were evaluated using one-way analysis of variance (ANOVA), and treatment means were separated using Duncan's Multiple Range Test (DMRT) where significant differences occurred. Pearson's correlation analysis was used to evaluate relationships between physicochemical variables and biodiversity indices. Statistical significance was accepted at $p<0.05$.

Ethical statement

This study complied with institutional guidelines for the use of experimental animals in research. Fish handling and sampling procedures were conducted in accordance with accepted ethical standards to minimise stress and unnecessary harm.

RESULTS

Rice yield, fish growth performance

The effects of the sole rice (RM) and integrated rice–fish (RF) culture systems on rice grain yield and the growth performance of *Clarias gariepinus* are presented in Table 2. Rice grain yield was significantly higher ($p<0.05$) in the integrated rice–fish culture system than in the sole rice system across all study locations. The highest rice grain yield (5.48 ± 0.23 t ha^{-1}) was recorded in the integrated rice–fish culture system at Onicha, whereas the lowest yield (4.11 ± 0.13 t ha^{-1}) occurred in the sole rice system at Ezza North.

Fish stocked in the integrated rice–fish culture system exhibited satisfactory growth throughout the study. Final weight, weight gain, survival rate and fish yield differed significantly ($P < 0.05$) among the study locations. The highest final weight (1,673.42 ± 58.94 g), weight gain (1,633.42 ± 58.94 g), survival rate (84.60 ± 1.94%), and fish yield (1,317.33 ± 41.67 kg ha^{-1}) were recorded at Onicha. No fish growth parameters were recorded in the sole rice treatment because fish were not stocked. These findings indicate that integrating fish into rice production enhanced rice productivity while simultaneously generating substantial fish biomass.

Physicochemical characteristics of water

The physicochemical characteristics of water under the sole rice (RM) and integrated rice–fish (RF) culture systems are presented in Table 3. Significant differences ($p<0.05$) were observed in several water quality variables between the two culture systems. The integrated rice–fish culture system recorded significantly higher pH (6.91 ± 0.19), dissolved oxygen (5.72 ± 0.41 mg L^{-1}), and transparency (34.67 ± 2.84 cm) than the sole rice culture system. In contrast, turbidity, ammonia, biological oxygen demand (BOD), and chemical oxygen demand (COD) were significantly lower in the integrated rice–fish culture system, indicating improved water quality.

Temperature, electrical conductivity, total dissolved solids, nitrate, and phosphate concentrations did not differ significantly ($p>0.05$) between the two culture systems. The higher dissolved oxygen and water transparency together with the lower turbidity and organic pollution indicators observed in the integrated rice–fish culture system, suggest that fish integration enhanced water quality and created more favourable environmental conditions for aquatic organisms.

Table 2. Rice grain yield and growth performance of *Clarias gariepinus* under sole rice (RM) and integrated rice–fish (RF) culture systems in Ebonyi State.

Study Location	Culture System	Rice Grain Yield (t ha⁻¹) Mean ± SD	Initial Weight (g) Mean ± SD	Final Weight (g) Mean ± SD	Weight Gain (g) Mean ± SD	Survival Rate (%) Mean ± SD	Fish Yield (kg ha⁻¹) Mean ± SD
Ezza North	RM	4.11 ± 0.13^b	–	–	–	–	–
	RF	5.24 ± 0.18^a	40.00 ± 5.18	$1{,}586.33 \pm 62.15^b$	$1{,}546.33 \pm 62.15^b$	81.20 ± 2.36^b	$1{,}241.00 \pm 34.52^b$
Onicha	RM	4.29 ± 0.17^b	–	–	–	–	–
	RF	5.48 ± 0.23^a	40.00 ± 5.18	$1{,}673.42 \pm 58.94^a$	$1{,}633.42 \pm 58.94^a$	84.60 ± 1.94^a	$1{,}317.33 \pm 41.67^a$
Afikpo South	RM	4.15 ± 0.16^b	–	–	–	–	–
	RF	5.39 ± 0.22^a	40.00 ± 5.18	$1{,}641.27 \pm 60.38^{ab}$	$1{,}601.27 \pm 60.38^{ab}$	83.10 ± 2.11^{ab}	$1{,}292.67 \pm 39.84^{ab}$
F-value		86.74	0.00	4.89	4.89	3.74	9.52
P-value		<0.001	1.000	0.034	0.034	0.048	<0.001

Note: Values are presented as Mean ± Standard Deviation (SD) of three independent replicates. Means within the same column bearing different superscript letters differ significantly (P < 0.05) according to Duncan's Multiple Range Test (DMRT). The dash (–) indicates that no fish were stocked in the sole rice (RM) treatment.

Table 3. Physicochemical characteristics of water under sole rice (RM) and integrated rice–fish (RF) culture systems in Ebonyi State

Parameter	RM (Mean ± SD)	RF (Mean ± SD)	F-value	P-value
Temperature (°C)	27.84 ± 0.48^a	27.63 ± 0.52^a	0.61	0.451
pH	6.58 ± 0.21^b	6.91 ± 0.19^a	8.46	0.017*
Dissolved oxygen (mg L⁻¹)	4.81 ± 0.34^b	5.72 ± 0.41^a	14.73	0.004*
Transparency (cm)	28.14 ± 2.18^b	34.67 ± 2.84^a	18.66	0.002*
Turbidity (NTU)	24.72 ± 2.13^a	18.65 ± 1.76^b	26.81	<0.001*
Electrical conductivity (µS cm⁻¹)	136.54 ± 6.18^a	132.37 ± 5.64^a	1.24	0.291
Total dissolved solids (mg L⁻¹)	82.63 ± 4.37^a	79.48 ± 4.02^a	1.62	0.232
Nitrate (mg L⁻¹)	1.86 ± 0.16^a	1.74 ± 0.18^a	1.15	0.308
Phosphate (mg L⁻¹)	0.52 ± 0.05^a	0.47 ± 0.04^a	2.19	0.170
Ammonia (mg L⁻¹)	0.31 ± 0.03^a	0.24 ± 0.02^b	19.52	0.001*
BOD (mg L⁻¹)	2.96 ± 0.22^a	2.37 ± 0.18^b	21.84	<0.001*
COD (mg L⁻¹)	18.42 ± 1.16^a	15.67 ± 1.04^b	17.45	0.003*

Values are Mean ± SD. Means with different superscript letters within a row differ significantly (DMRT, p < 0.05).

Interpretation of water quality

Water temperature remained relatively stable between the two production systems and did not differ significantly (*P* = 0.451), indicating that fish integration had little influence on the thermal characteristics of the rice fields.

In contrast, the integrated rice–fish system maintained significantly higher pH (6.91 ± 0.19) and dissolved oxygen (5.72 ± 0.41 mg L⁻¹) than the rice monocropping system (6.58 ± 0.21 and 4.81 ± 0.34 mg L⁻¹, respectively). Likewise, water transparency increased significantly in RF plots (34.67 ± 2.84 cm) relative to RM plots (28.14 ± 2.18 cm). These findings indicate that integrating fish improved water quality by promoting aeration, nutrient cycling, and sediment mixing.

Conversely, turbidity, ammonia, biochemical

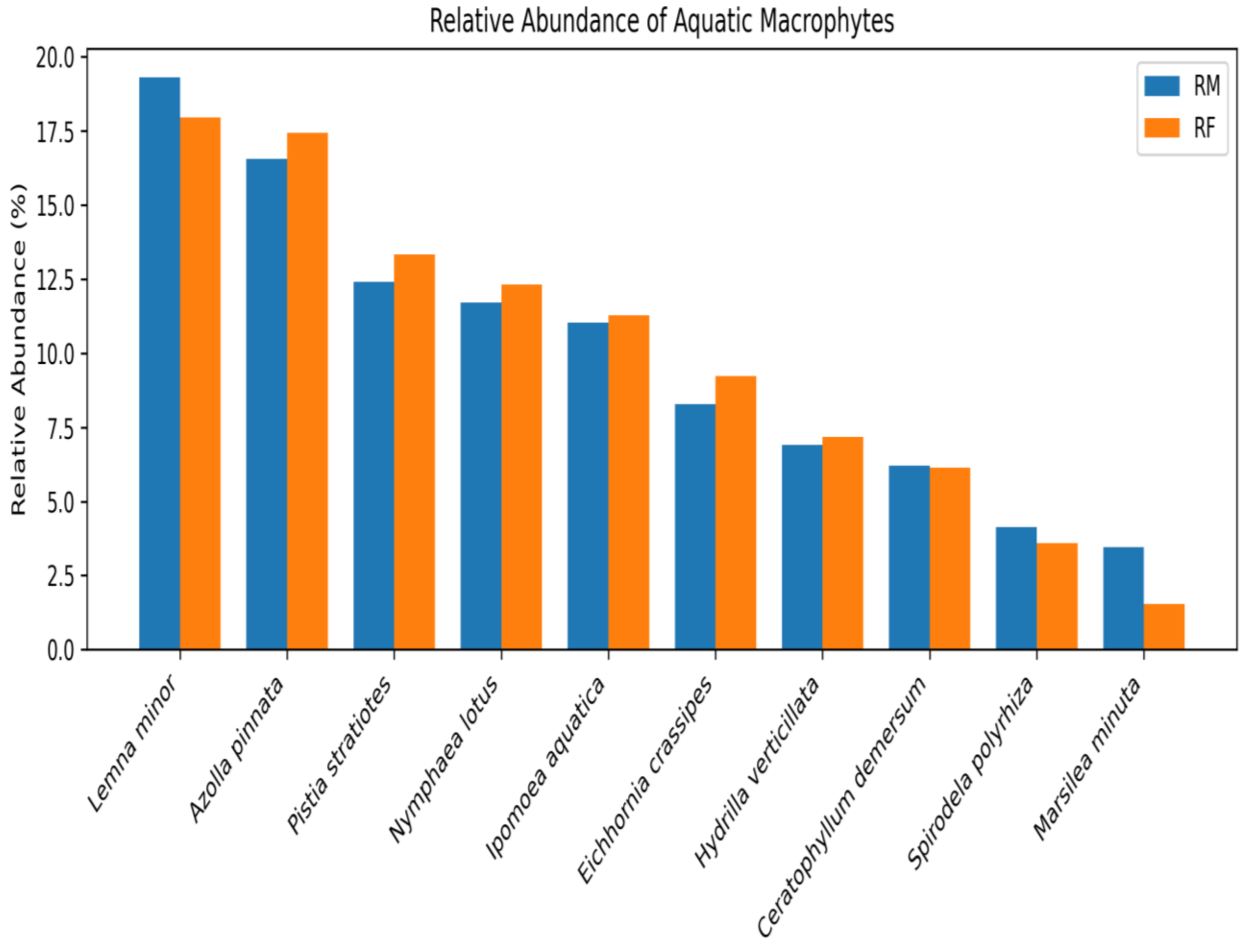

Figure 1. Relative abundance of aquatic macrophytes under sole rice (RM) and integrated rice–fish (RF) culture systems.

oxygen demand (BOD), and chemical oxygen demand (COD) were significantly lower in the integrated rice–fish system than in the monocropping system ($P < 0.05$). Lower turbidity and reduced organic loading suggest improved ecological functioning and greater decomposition efficiency within the integrated production system.

Electrical conductivity, total dissolved solids, nitrate, and phosphate concentrations did not differ significantly between treatments ($p>0.05$), indicating that fish integration enhanced ecological processes without causing excessive nutrient accumulation or deterioration in water chemistry.

These results demonstrate that integrating fish into rice production improved key physicochemical characteristics while maintaining environmental conditions suitable for sustaining diverse aquatic communities.

Aquatic macrophyte diversity

The relative abundance of aquatic macrophytes under the sole rice (RM) and integrated rice–fish (RF) culture systems is presented in Figure 1. A total of ten aquatic macrophyte species were identified across the study sites, comprising floating, emergent and submerged aquatic plants. The integrated rice–fish culture system supported a greater abundance and a more even distribution of aquatic macrophytes than the sole rice culture system.

Among the species recorded, *Lemna minor* was the most abundant in both culture systems, accounting for 19.31% and 17.95% of the total macrophyte population in RM and RF, respectively. *Azolla pinnata* was the second most abundant species, contributing 16.55% in RM and 17.44% in RF. Similarly, *Pistia stratiotes*, *Nymphaea lotus*, *Ipomoea aquatica*, *Eichhornia crassipes* and *Hydrilla verticillata* were more abundant in the integrated rice–fish culture system than in the sole rice system. In contrast, *Spirodela polyrhiza* and *Marsilea minuta* occurred at relatively lower abundances in both culture systems.

The higher abundance and broader distribution of aquatic macrophytes observed in the integrated rice–fish culture system indicate that fish integration enhanced habitat heterogeneity and improved environmental conditions favourable for aquatic plant establishment and growth.

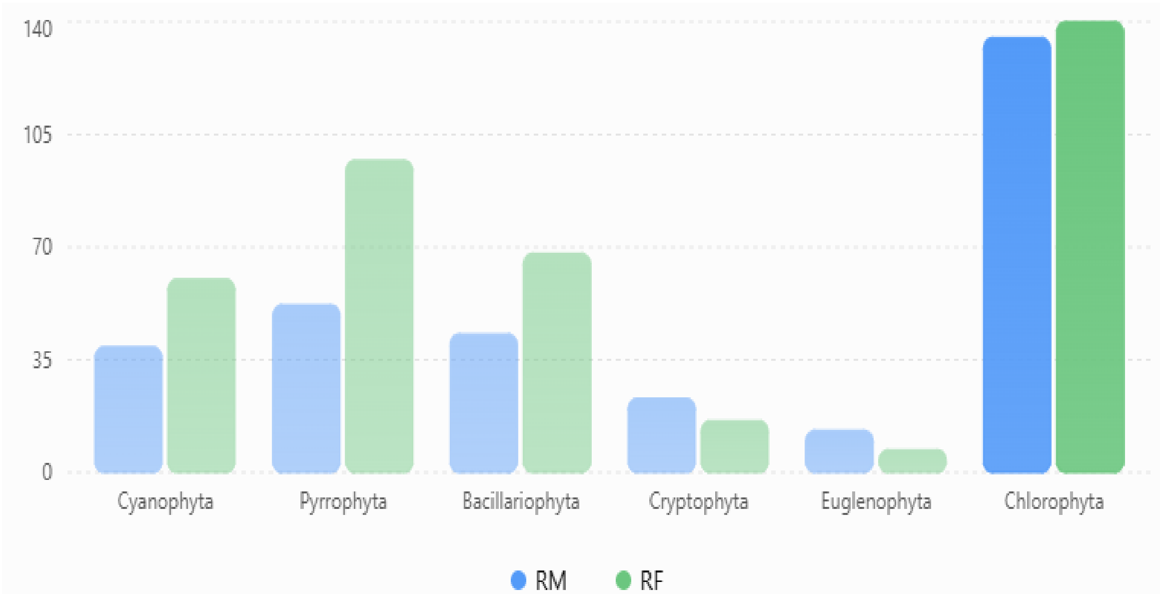

Figure 2. Composition of phytoplankton by taxonomic division under sole rice (RM) and integrated rice–fish (RF) culture systems.

Comparative assessment of phytoplankton under Sole Rice (RM) and Integrated Rice–Fish (RF) culture systems

The cumulative abundance of the major phytoplankton divisions recorded under the sole rice (RM) and integrated rice–fish (RF) culture systems is presented in Figure 2. Chlorophyta was the most abundant phytoplankton division in both culture systems, with a total abundance of 135 individuals in RM and 140 individuals in RF. Pyrrophyta constituted the second most abundant division and was markedly higher in the integrated rice–fish culture system (97 individuals) than in the sole rice system (52 individuals). Similarly, Bacillariophyta and Cyanophyta were more abundant under the integrated rice–fish culture system, recording 68 and 60 individuals, respectively, compared with 43 and 39 individuals in the sole rice system. In contrast, Cryptophyta and Euglenophyta exhibited relatively low abundances in both culture systems, although Cryptophyta was slightly higher in RM (23 individuals) than RF (16 individuals), while Euglenophyta recorded 13 individuals in RM and 7 individuals in RF. These results indicate that the integrated rice–fish culture system supported a greater abundance of the dominant phytoplankton divisions than the sole rice culture system.

Zooplankton community composition and dominant species

The composition of zooplankton recorded under the sole rice (RM) and integrated rice–fish (RF) culture systems is presented in Figure 3. Four major zooplankton groups were identified during the study, namely Protozoa, Rotifera, Cladocera and Copepoda. The integrated rice–fish culture system supported a greater abundance of most zooplankton groups than the sole rice culture system, indicating that fish integration enhanced environmental conditions favourable for zooplankton development.

Rotifera constituted the dominant zooplankton group in both culture systems, followed by Cladocera and Copepoda, while Protozoa occurred at comparatively lower abundance. Members of the genera *Brachionus*, *Keratella*, *Lecane* and *Filinia* were the most frequently encountered rotifers, whereas *Daphnia*, *Bosmina* and *Ceriodaphnia* represented the dominant cladocerans. The copepod community was dominated by *Cyclops*, *Mesocyclops* and *Eucyclops* species.

The higher abundance of Rotifera, Cladocera and Copepoda observed in the integrated rice–fish culture system suggests that improved water quality and enhanced nutrient cycling promoted greater zooplankton productivity compared with the sole rice culture system.

Zoobenthic community composition and dominant species

The composition and relative abundance of the zoobenthic community recorded under the sole rice (RM) and integrated rice–fish (RF) culture systems are presented in Table 4. A total of 11 zoobenthic species belonging to three major taxonomic groups, namely Insecta, Oligochaeta, and Mollusca (Gastropoda), were identified during the study. The integrated rice–fish (RF) culture

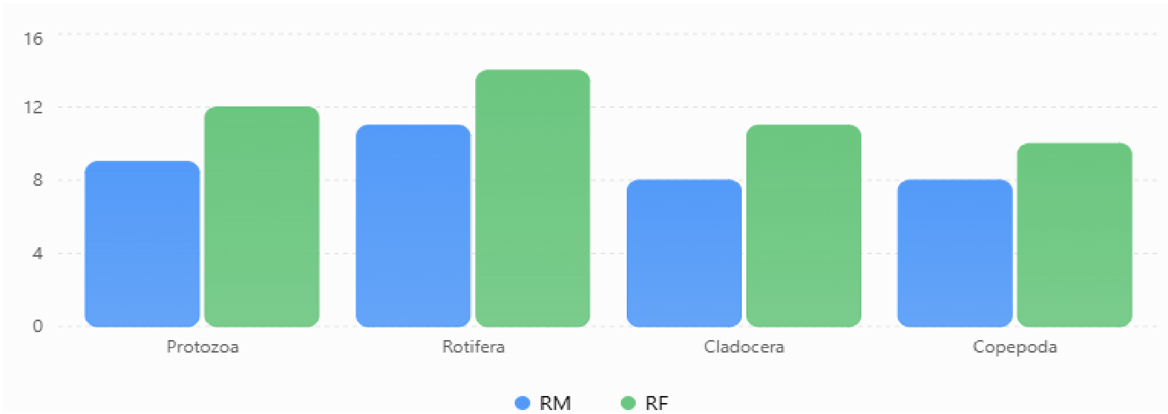

Figure 3. Composition of zooplankton by taxonomic group under sole rice (RM) and integrated rice–fish (RF) culture systems.

Table 4. Composition of zoobenthic community under sole rice (RM) and integrated rice–fish (RF) culture systems.

Taxonomic Group	Species	RM (N)	RM (%)	RM Status	RF (N)	RF (%)	RF Status
Insecta	*Chironomus austini*	38	18.18	Dominant	42	16.15	Dominant
	Chironomus staegeri	31	14.83	Common	35	13.46	Common
	Chironomus kiefferulus	24	11.48	Common	30	11.54	Common
	Glyptotendipes sp.	19	9.09	Common	25	9.62	Common
Oligochaeta	*Limnodrilus hoffmeisteri*	27	12.92	Common	32	12.31	Common
	Branchiura sowerbyi	18	8.61	Less dominant	24	9.23	Common
	Nais sp.	16	7.66	Less dominant	21	8.08	Less dominant
Mollusca (Gastropoda)	*Melanoides tuberculata*	14	6.70	Less dominant	22	8.46	Common
	Lanistes varicus	11	5.26	Rare	16	6.15	Less dominant
	Bulinus globosus	8	3.83	Rare	10	3.85	Rare
	Biomphalaria pfeifferi	3	1.44	Rare	3	1.15	Rare
Total	11 Species	209	100.00		260	100.00	

Note: RM = Sole Rice Culture System; RF = Integrated Rice–Fish Culture System; N = Number of Individuals; Relative abundance (%) = (Number of individuals of a species ÷ Total number of individuals recorded in each culture system) × 100.

system supported a higher abundance of zoobenthic organisms (260 individuals) than the sole rice (RM) system (209 individuals), indicating that fish integration enhanced the suitability of the benthic habitat.

The zoobenthic community was dominated by members of the Insecta, with *Chironomus austini* recording the highest abundance in both culture systems. This species accounted for 18.18% of the total individuals in RM and 16.15% in RF and was classified as the dominant species in both systems. Other insect taxa, including *Chironomus staegeri*, *Chironomus kiefferulus*, and *Glyptotendipes* sp., also occurred in relatively high abundances and constituted an important component of the benthic fauna.

The Oligochaeta were represented by *Limnodrilus hoffmeisteri*, *Branchiura sowerbyi*, and *Nais* sp. *Limnodrilus hoffmeisteri* was the most abundant oligochaete species, contributing 12.92% and 12.31% of the total zoobenthic community in the RM and RF systems, respectively. The abundance of *Branchiura sowerbyi* and *Nais* sp. was greater in the integrated rice–fish culture system, suggesting that the improved sediment conditions favoured the establishment and proliferation of these benthic organisms.

Members of the Mollusca (Gastropoda) included *Melanoides tuberculata*, *Lanistes varicus*, *Bulinus globosus*, and *Biomphalaria pfeifferi*. *Melanoides tuberculata* was the most abundant gastropod species, increasing from 14 individuals (6.70%) in the RM system to 22 individuals (8.46%) in the RF system. In contrast, *Biomphalaria pfeifferi* was the least abundant species, with only three individuals recorded in each culture system.

The integrated rice–fish culture system supported higher

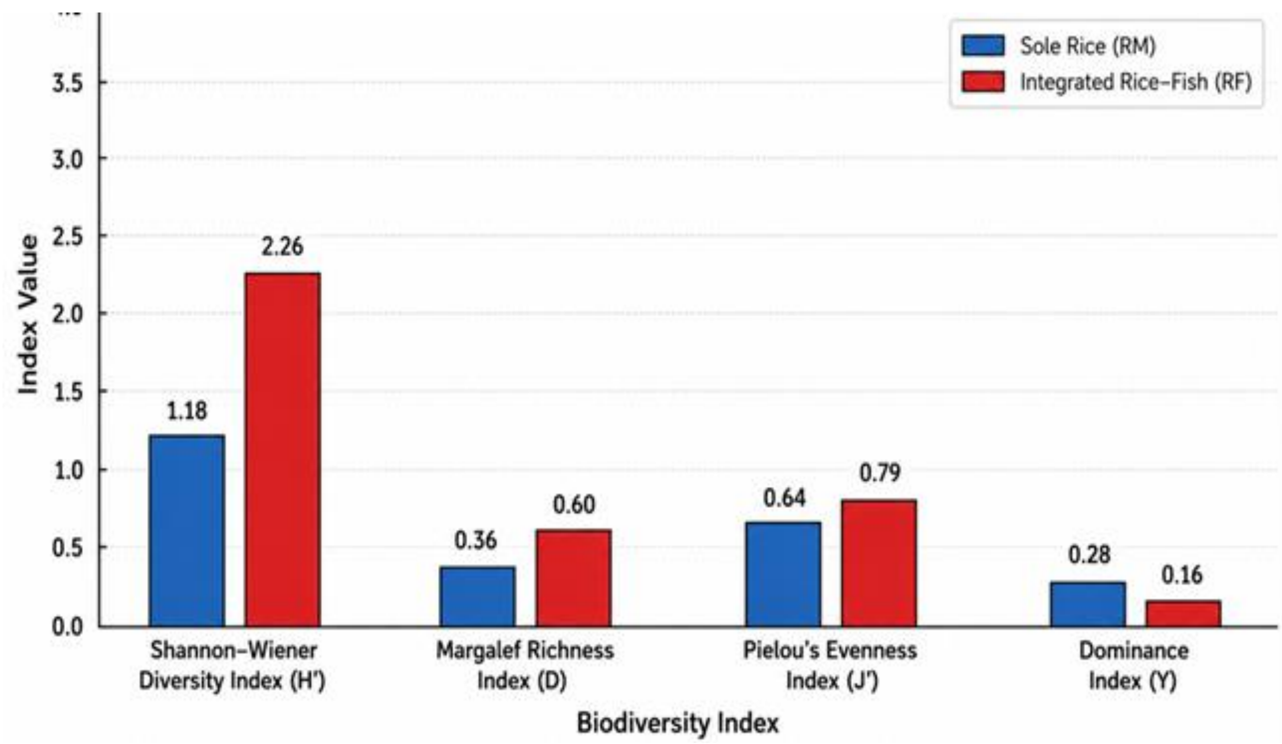

Figure 4. Comparison of aquatic biodiversity indices under sole rice (RM) and integrated rice–fish (RF) culture systems.

abundances for most zoobenthic species than the sole rice culture system. The greater abundance of benthic macroinvertebrates observed in the integrated system suggests that fish integration improved sediment quality, increased organic matter decomposition, and enhanced food availability for benthic organisms. These conditions promoted the development of a more abundant and better-distributed zoobenthic community than that observed in the rice monoculture system.

Aquatic biodiversity indices

The aquatic biodiversity indices of the sole rice (RM) and integrated rice–fish (RF) culture systems are presented in Figure 4. The integrated rice–fish culture system generally exhibited higher biodiversity index values than the sole rice system, indicating a more diverse and ecologically balanced aquatic community. Shannon–Wiener diversity, Margalef richness, and Pielou's evenness indices were consistently greater in the integrated culture system, reflecting improved species diversity, richness, and distribution. Conversely, the dominance index was comparatively lower in the integrated rice–fish system, suggesting reduced dominance by a few species and a more equitable distribution of organisms within the aquatic community. These findings demonstrate that integrating fish into rice fields enhanced biodiversity and promoted greater ecological stability than rice monoculture.

DISCUSSION

Rice grain yield and growth performance

The integrated rice–fish (RF) system produced significantly higher rice grain yields than rice monocropping (RM) across all three study locations. Yield increased from 4.11 ± 0.13 to 5.24 ± 0.18 t ha^{-1} at Ezza North, from 4.29 ± 0.17 to 5.48 ± 0.23 t ha^{-1} at Onicha, and from 4.15 ± 0.16 to 5.39 ± 0.22 t ha^{-1} at Afikpo South, with the highest RF yield recorded at Onicha. The consistent improvement across locations indicates that fish integration enhanced resource utilisation within the rice fields. Fish activity can promote sediment disturbance, nutrient redistribution and organic matter turnover, thereby improving nutrient availability to rice. The finding is consistent with Ling Ling *et al*. (2024), who reported positive effects of rice–fish integration on rice production and resource-use efficiency in African farming systems.

Fish production was also substantial in the integrated system. *Clarias gariepinus* recorded the highest final weight (1,673.42 ± 58.94 g), weight gain (1,633.42 ± 58.94 g), survival rate (84.60 ± 1.94%), and fish yield (1,317.33 ± 41.67 kg ha^{-1}) at Onicha, indicating that the rice-field environment provided suitable conditions for fish growth and survival. The availability of plankton and benthic organisms recorded in the present study may have contributed to the natural food base, while supplementary feeding further supported fish growth. Similar benefits of integrated rice–fish production for fish growth and overall farm productivity have been reported by Ling Ling *et al*. (2024) and Hou *et al*. (2024).

The significant differences among locations indicate that local environmental conditions influenced production performance, particularly fish growth. However, the consistently higher rice yield under RF across the three locations demonstrates that the benefits of integration were maintained under different field conditions. Producing rice and fish within the same production unit therefore offers an opportunity to increase food output and improve resource-use efficiency without requiring separate land for fish production.

Physicochemical water characteristics

The integrated rice–fish (RF) system produced a generally more favourable water-quality profile than rice monocropping (RM). Dissolved oxygen and pH were significantly higher in RF plots (5.72 ± 0.41 mg L^{-1} and 6.91 ± 0.19, respectively) than in RM plots (4.81 ± 0.34 mg L^{-1} and 6.58 ± 0.21), while water transparency was also significantly greater under RF (34.67 ± 2.84 cm) than RM (28.14 ± 2.18 cm). In contrast, turbidity, ammonia, BOD, and COD were significantly lower in the integrated system. These differences indicate that fish integration improved several important aspects of the aquatic environment while avoiding excessive nutrient accumulation.

The higher dissolved oxygen and transparency recorded under RF provide favourable conditions for plankton and other aquatic organisms and may partly explain the greater biological diversity observed in the integrated plots. Fish movement, nutrient redistribution, and interactions among fish, rice plants, microorganisms, and aquatic organisms may have contributed to these changes. The lower BOD, COD, and ammonia concentrations further suggest more efficient processing of organic materials and nitrogenous wastes within the integrated system. Recent research on rice–fish integration similarly demonstrates that interactions between aquaculture and rice production can modify water and sediment conditions and influence aquatic ecosystem functioning (Hou *et al*., 2024; Diao *et al*., 2024).

Not all parameters responded significantly to fish integration. Temperature, electrical conductivity, total dissolved solids, nitrate, and phosphate showed no significant differences between RF and RM systems. This indicates that the improved water-quality profile of RF was not associated with a general increase in dissolved nutrients. Instead, the response was expressed mainly through improved oxygen conditions, greater transparency, and reduced indicators of organic and nitrogenous loading. The present results therefore suggest that integrating *Clarias gariepinus* into rice cultivation improved key physicochemical conditions while maintaining relatively stable concentrations of other water-quality variables, thereby providing a suitable environment for the diverse aquatic communities recorded in the study.

Aquatic macrophyte diversity

The greater aquatic macrophyte richness and abundance recorded in the integrated rice–fish (RF) system indicate that fish integration was associated with greater vegetation diversity than rice monocropping (RM). This finding is consistent with the ecological differences observed between the two production systems, particularly the higher dissolved oxygen and transparency and lower turbidity and organic loading recorded under RF. The presence of fish may also have modified sediment conditions and nutrient redistribution, creating heterogeneous microsites that supported the establishment of different macrophyte species. A recent review of rice–fish co-culture systems similarly identified biodiversity conservation and improved ecological functioning as important environmental benefits of integration (Fan *et al*., 2025).

The richer macrophyte assemblage under RF is ecologically important because aquatic vegetation provides structural habitat and contributes to nutrient uptake, sediment stabilisation and food-web support. These functions can increase habitat heterogeneity for plankton, benthic organisms and juvenile fish. Evidence from rice–fish mixed farming has also shown that differences in vegetation composition can occur between fields with and without fish habitats, indicating that the physical and biological conditions created by fish integration can influence plant-community structure.

The comparatively lower macrophyte diversity under RM therefore suggests that the simpler ecological conditions in the monocropping system supported fewer aquatic plant niches. However, the present study does not establish that fish integration directly caused the increase in every macrophyte species. Rather, the observed pattern, together with the improved physicochemical conditions measured in RF, indicates that integration created conditions associated with greater aquatic vegetation diversity. This greater vegetation diversity may consequently have contributed to the habitat complexity and biological productivity of the integrated rice–fish system.

Phytoplankton diversity

The higher phytoplankton richness and diversity recorded in the integrated rice–fish (RF) system indicate that fish integration was associated with greater primary-producer diversity than rice monocropping (RM). Chlorophyta was the dominant group in both systems, followed by Bacillariophyta, Cyanophyta, Pyrrophyta, Euglenophyta and Cryptophyta, with the RF system generally supporting the richer assemblage. This pattern is consistent with the improved water-quality conditions recorded under RF, particularly the significantly higher dissolved oxygen and transparency and lower turbidity, ammonia, BOD and COD. The combination of these conditions with continuous biological interactions within the flooded fields likely provided a more suitable environment for phytoplankton development.

The present finding is supported by Welde *et al*. (2024), who directly compared rice–carp coculture with rice monoculture and found higher phytoplankton richness, diversity and evenness in the integrated system during the grain-filling stage. Their study also demonstrated that rice–fish integration altered the composition and abundance of dominant plankton groups, indicating that fish integration can modify the aquatic food environment of rice fields. Kouadio *et al*. (2025) reported similar relationships between agricultural inputs and phytoplankton functional groups in rice–fish systems.

The dominance of Chlorophyta and Bacillariophyta in the present study is ecologically relevant because these groups constitute important primary producers and provide food resources for higher trophic levels. Their greater representation in the RF system may therefore have contributed to the higher zooplankton abundance recorded in the same treatment. This trophic connection is important because the phytoplankton community provides the primary biological resource supporting secondary consumers in flooded rice fields. The 2024 rice–carp study similarly demonstrated that changes in phytoplankton communities under coculture were accompanied by changes in microzooplankton communities, highlighting the interconnected nature of these planktonic assemblages.

The comparatively lower phytoplankton diversity under RM suggests that the absence of fish resulted in a less biologically interactive aquatic environment. However, the present study does not establish that fish activity alone caused the differences in every phytoplankton group. Rather, the consistent pattern, together with the observed differences in water quality and the greater diversity of other aquatic communities under RF, supports the interpretation that rice–fish integration enhanced the ecological conditions associated with phytoplankton development. Recent evidence that integrated rice–fish systems modify aquatic microbial communities and environmental conditions further supports this interpretation (Diao *et al*., 2024).

Overall, the phytoplankton results demonstrate that the RF system supported a more diverse primary-producer community than RM. This provides an important ecological link between the improved physicochemical conditions recorded in the integrated fields and the higher zooplankton and fish productivity observed in the present study.

Zooplankton diversity

The higher zooplankton richness and abundance recorded in the integrated rice–fish (RF) system indicate that fish integration was associated with a more productive planktonic community than rice monocropping (RM). The pattern corresponds with the higher phytoplankton diversity recorded under RF in the present study and with the improved water-quality conditions, particularly the higher dissolved oxygen and transparency and lower turbidity, ammonia, BOD and COD. These conditions provide a more favourable environment for zooplankton development and may have strengthened the transfer of energy from primary producers to higher trophic levels.

The dominance of Rotifera, Cladocera and Copepoda in the present study is consistent with the typical composition of freshwater zooplankton communities. Their greater representation in the RF system suggests that fish integration did not simply increase fish production at the expense of lower trophic organisms. Rather, the integrated fields supported a sufficiently productive planktonic food base to sustain both zooplankton and fish. Welde *et al*. (2024) similarly reported differences in phytoplankton and microzooplankton communities between rice–carp coculture and rice monoculture, demonstrating that fish integration can modify plankton-community structure within flooded rice fields.

The comparatively lower zooplankton diversity under RM is consistent with the lower phytoplankton diversity observed in the same system. Because many rotifers, cladocerans and other zooplankton depend directly or indirectly on primary producers, reduced phytoplankton availability can constrain secondary productivity. The relationship observed in the present study therefore suggests a connected trophic response in which improved conditions under RF supported primary producers and, subsequently, their consumers. Recent investigations of rice-field zooplankton have also demonstrated that community composition is strongly associated with local environmental conditions and habitat characteristics (Maiphae *et al*., 2023; Dewi *et al*., 2025).

The differences among locations indicate that local environmental conditions also influenced zooplankton composition. Nevertheless, the greater diversity recorded under RF across the study locations suggests that the effect of the integrated production environment was consistent despite spatial variation. The richer zooplankton community may have contributed to the natural food resources available to *Clarias gariepinus*, providing a plausible ecological link between the plankton results and the superior fish growth recorded in the RF system. Overall, the present findings indicate that rice–fish integration strengthened the planktonic food web and enhanced the biological complexity of the rice-field ecosystem.

Zoobenthic (Benthic macroinvertebrate) diversity

The integrated rice–fish (RF) system supported a richer and more diverse benthic macroinvertebrate community than rice monocropping (RM), indicating greater benthic habitat complexity under the integrated production system. This finding is important because benthic macroinvertebrates respond to differences in habitat structure and environmental conditions and can therefore provide useful information on ecological status. Recent research in rice-paddy ecosystems has similarly demonstrated that farming practices and habitat characteristics influence benthic macroinvertebrate richness, diversity and community structure (Kim and Kim, 2025).

The greater benthic diversity under RF may be associated with the physical and biological interactions created by fish integration. Fish movement can disturb surface sediments and redistribute organic materials, while rice roots, aquatic vegetation and accumulated organic matter provide different microhabitats for benthic organisms. The present study recorded insect larvae, molluscs, annelids and annelids among the benthic assemblage, indicating that the integrated fields supported organisms occupying different ecological niches. However, because sediment characteristics and benthic habitat variables were not measured sufficiently to establish direct causal relationships, these mechanisms should be regarded as plausible explanations rather than definitive causes.

The lower benthic diversity under RM is consistent with the comparatively simpler biological conditions of the monocropping system. The greater diversity under RF also has implications for fish production because benthic organisms constitute part of the natural food resources available to *Clarias gariepinus*. Thus, the richer benthic community observed under RF provides an additional ecological pathway linking habitat conditions with the superior fish performance recorded in the integrated system. The importance of benthic communities to ecosystem functioning and their sensitivity to environmental conditions has also been demonstrated in recent freshwater studies (Ouma *et al*., 2025; Olowo *et al*., 2025).

Differences among locations indicate that local environmental conditions also influenced benthic community structure. Nevertheless, the greater diversity associated with RF demonstrates that the integrated production system supported more complex benthic communities across the study area. Overall, the present findings suggest that rice–fish integration enhanced sediment-associated biodiversity while simultaneously providing additional natural food resources for fish, thereby strengthening the ecological functioning of the rice-field ecosystem.

Biodiversity Indices

The biodiversity indices recorded in the present study consistently indicated a more diverse and evenly structured aquatic community under the integrated rice–fish (RF) system than under rice monocropping (RM). The higher Shannon–Wiener diversity values in RF indicate that the integrated fields supported a broader distribution of individuals among the recorded taxa, rather than being dominated by a small number of species. This pattern aligns with the greater diversity observed among phytoplankton, zooplankton, aquatic macrophytes, and benthic macroinvertebrates in the integrated system.

Higher Margalef richness values under RF further demonstrate that fish integration was associated with greater taxonomic richness. This result is consistent with the greater number of aquatic organisms recorded across the biological components of the integrated fields. The presence of fish, rice plants, aquatic macrophytes, plankton and benthic habitats may have increased the number of ecological niches available within the production system. Recent assessments of rice–fish systems have similarly identified increased biological diversity and ecological complexity among important environmental outcomes of integration (Ling Ling *et al*., 2024; Fan *et al*., 2025).

Pielou's evenness was also higher under RF, indicating a more balanced distribution of individuals among taxa. Conversely, the lower dominance values recorded in the integrated system suggest that the communities were less strongly controlled by a few dominant taxa. Taken together, the Shannon–Wiener, Margalef's richness, Pielou's evenness and dominance results provide complementary evidence that the RF system supported a more heterogeneous and balanced aquatic community than RM.

The differences in biodiversity indices are consistent with the physicochemical and biological patterns observed in this study. The RF system recorded higher dissolved oxygen and transparency and lower turbidity, ammonia, BOD and COD, while also supporting richer phytoplankton, zooplankton, macrophyte and benthic communities. These results suggest that the improved environmental conditions associated with RF were accompanied by greater aquatic biodiversity. However, the indices themselves describe community structure and do not establish direct causal relationships between individual water-quality parameters and diversity.

Overall, the biodiversity indices strengthen the evidence that integrating *Clarias gariepinus* with rice cultivation increased the ecological complexity of the production system. The simultaneous improvement in species richness, diversity and evenness, together with reduced dominance, indicates that RF provided a more heterogeneous aquatic environment than conventional rice monocropping. This finding supports the ecological value of rice–fish integration as a production approach that can combine agricultural productivity with the maintenance of aquatic biological diversity.

Recommendations

Based on the findings of this study, integrated rice–fish farming using Clarias gariepinus is recommended as a resource-efficient production strategy in suitable rice-growing areas of Ebonyi State. The system should be promoted where water availability and field conditions can support both rice and fish production while maintaining favourable aquatic environmental conditions.

Farmers adopting the integrated system should give attention to site-specific management, particularly water depth, water quality, fish stocking and field characteristics. Management practices should be adapted to local conditions because differences among Ezza North, Onicha and Afikpo South showed that environmental conditions can influence production outcomes.

Further research is recommended to assess seasonal and longer-term responses of water quality and aquatic biodiversity and to evaluate different fish stocking densities. Future studies should also examine relationships between specific environmental variables and individual aquatic communities to better explain the mechanisms underlying the observed biodiversity patterns.

Overall, the findings support the ecological and production value of integrating Clarias gariepinus with rice cultivation in Ebonyi State, particularly where the system can be managed to maintain favourable water-quality conditions and aquatic biodiversity.

Conclusion

The present study demonstrated that integrating fish into rice production improved both agricultural productivity and aquatic ecosystem quality in Ebonyi State, Nigeria. The integrated rice–fish culture system produced significantly higher rice grain yield while supporting satisfactory growth and survival of *Clarias gariepinus*. Fish integration also improved several important water quality parameters, including dissolved oxygen, transparency and pH, while reducing turbidity, ammonia, biological oxygen demand and chemical oxygen demand.

The integrated culture system supported greater abundance and diversity of aquatic macrophytes, phytoplankton, zooplankton and zoobenthic organisms than the sole rice culture system. Biodiversity indices further confirmed that integrating fish into rice fields promoted higher species diversity, richness and community evenness while reducing species dominance. These findings demonstrate that integrated rice–fish farming provides a more productive and ecologically sustainable production system than rice monoculture. The adoption of integrated rice–fish farming can therefore contribute to improved food production, biodiversity conservation and sustainable agricultural development.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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