

Rice–fish co-culture systems: yield, production, advantages and limitations

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Abstract. Rice–fish co-culture represents a historically rooted and ecologically integrated agricultural system that combines rice cultivation with the rearing of aquatic organisms within the same production unit. This review synthesizes current knowledge on the yield performance, ecological functions, biogeochemical processes, and socio-economic implications of rice–fish systems across diverse geographical contexts. Evidence indicates that such systems can maintain or enhance rice yields while providing additional aquatic outputs, thereby increasing overall productivity and farm profitability. Ecologically, rice–fish co-culture promotes biological pest control, improves soil fertility, enhances nutrient cycling, and reduces reliance on chemical inputs. The system functions as a dynamic biogeochemical unit in which interactions between plants, aquatic organisms, and microbial communities regulate nutrient availability and ecosystem stability. Furthermore, rice–fish systems exhibit significant potential for climate change adaptation through diversification, hydrological buffering, and microclimatic regulation. However, constraints such as improper management, environmental conditions, and socio-economic barriers can limit their effectiveness. This review highlights both the opportunities and challenges associated with rice–fish co-culture, emphasizing its role as a model for sustainable agricultural intensification.

Key Words: rice–fish co-culture, integrated agriculture–aquaculture, ecological intensification, nutrient cycling, agroecosystems, sustainable agriculture, biogeochemical processes, ecosystem services, climate resilience, aquaculture systems.

Introduction. Rice–fish co-culture integrates paddy rice with fish or other aquatic animals (both food and ornamental species) in the same water and land resource. Research spans traditional systems in Asia, crayfish and prawn variants, ex situ or pond-based models, and emerging systems with ornamental koi carp, focusing on productivity, ecosystem services, and sustainability (Wan et al 2019; Hou et al 2020; Arunrat & Sereenonchai 2022; Li et al 2024ab; Hu et al 2016; Xie et al 2011; Kaewpuangdee et al 2024; Jia et al 2025; Jin-Fei et al 2016).

The aim of this review is to provide a comprehensive and integrative analysis of rice–fish co-culture systems by examining their historical development, production performance, ecological and agronomic benefits, mechanistic interactions, and biogeochemical dynamics. Additionally, the review seeks to evaluate the socio-economic implications and climate resilience potential of these systems, while critically assessing their limitations and constraints. By synthesizing recent empirical and theoretical research, this work aims to clarify the role of rice–fish co-culture as a sustainable agricultural strategy and to identify key factors influencing its successful implementation and scalability.

Methodology. This review was conducted using a structured literature search strategy aimed at identifying relevant publications on rice–fish co-culture systems. Scientific databases including PubMed, Scopus, and Google Scholar were systematically explored using combinations of keywords related to rice–fish integration, aquaculture, agroecosystems, and sustainability.

Given the extensive body of literature available on this topic, a set of inclusion criteria was applied to ensure the relevance and quality of the selected studies. Eligible publications were required to (i) address rice–fish co-culture or closely related integrated systems, (ii) be published in peer-reviewed journals, (iii) be available in English, and (iv) provide sufficient methodological or empirical detail to support comparative analysis. Studies lacking clear relevance or adequate scientific rigor were excluded.

In addition to database searches, citation tracking and reference list screening were employed to identify further pertinent studies. This approach allowed the inclusion of both foundational and recent contributions, ensuring a comprehensive and balanced synthesis of the existing literature while minimizing potential selection bias.

The Historical Origins and Development of Rice–Fish Co-Culture. Rice–fish co-culture is one of the oldest known forms of integrated agriculture–aquaculture, in which fish are deliberately reared in flooded rice fields. Archaeological, paleoenvironmental, and historical evidence indicate that its roots lie in the Neolithic transformation of wetlands in the Yangtze basin of China, where Austroasiatic communities began to exploit emerging lacustrine and swamp environments about 8000 BC, gathering wild rice and fish and gradually shifting from hunting–gathering–fishing to coupled rice and fish farming (Edwards 2025). As inland lakes, marshes, and wild rice stands expanded at the end of the last glacial period, these communities developed a mixed subsistence strategy that set the ecological and cultural preconditions for later intentional rice–fish farming (Edwards 2025).

China is widely regarded as the primary cradle of rice–fish co-culture and of aquaculture more broadly. Early textual references include oracle bone inscriptions from the Shang dynasty (ca. 1600–1046 BC) that record pond fish culture, and later the treatise attributed to Fan Li (ca. 5th century BC), often cited as the first systematic account of carp farming (Edwards 2025). Over subsequent dynasties, policies and cultural norms shaped species choice: for example, a Tang dynasty prohibition on farming common carp because its name coincided with that of the ruling Li family is thought to have stimulated the diversification of Chinese carp polyculture (Edwards 2025). By at least 1700 years ago, deliberate integration of fish into rice paddies was widespread in parts of south China, forming distinctive agro landscapes in terraced and lowland systems (Lu & Li 2006; Xie et al 2011; Halwart & Gupta 2004).

Within this long trajectory, specific regional configurations acquired heritage status. The terraced rice–fish system of Qingtian County in Zhejiang Province has been practiced continuously for roughly 1200 years (Xie et al 2011; Li et al 2025; Halwart & Gupta 2004). In this system, indigenous deep water rice varieties and local Oujiang red carp or “paddy field carp” are co-cultured in stepped terraces, creating a mosaic landscape in which thousands of smallholder households maintain interlinked stocks of fish and seeds (Lu & Li 2006; Xie et al 2011; Ren et al 2018). Genetic studies of the paddy field carp in this 1200 year old system show that farmers’ practices of exchanging broodstock and mixed culturing of diverse colour types have preserved high levels of genetic diversity and structured yet interconnected metapopulations, illustrating how traditional management has co evolved with local biota (Li et al 2024ab; Ren et al 2018).

Over time, rice–fish systems in China diversified beyond simple rice–carp associations. Historical and contemporary surveys describe rice–fish–duck symbiosis, in which ducks forage in paddies alongside rice and fish, and other multi trophic combinations that have been recognized by FAO and UNESCO as Globally Important Agricultural Heritage Systems (GIAHS) (Zhang et al 2023ab; Lu & Li 2006; Xie et al 2011; Freed et al 2020; Ge et al 2023; Wang et al 2022). These systems embody cumulative ecological knowledge about synchronizing cropping calendars, water management, and species interactions so that fish help regulate weeds and insect pests,

rice moderates the aquatic environment, and, in some variants, ducks contribute additional nutrient cycling and pest control (Zhang et al 2023ab; Lu & Li 2006; Xie et al 2011; Wan et al 2019; Frei & Becker 2005; Ge et al 2023).

Although the earliest documented and most intensively studied rice–fish co-cultures are Chinese, analogous integrated rice field aquaculture developed across much of tropical and subtropical Asia. Historical syntheses and global reviews describe rice–fish farming as a long standing practice in South and Southeast Asian rice landscapes, later transformed but not entirely displaced by the Green Revolution and the expansion of specialized pond and cage aquaculture (Lu & Li 2006; Freed et al 2020; Frei & Becker 2005; Halwart & Gupta 2004). In India, for example, reviews refer to traditional rice–fish systems that pre date modern intensification and have persisted in various modified forms, while in Cambodia and Vietnam, extensive rice field fisheries and rice–shrimp systems represent locally adapted expressions of rice–aquatic animal integration (Sathoria & Roy 2022; Freed et al 2020; Frei & Becker 2005; Halwart & Gupta 2004).

From the late twentieth century onward, scientific and policy attention reframed these historically rooted practices as models of ecological intensification and sustainable food production. Rice–fish systems began to be systematically documented as low external input agro ecosystems that could maintain rice yields while reducing fertilizer and pesticide use, conserving agrobiodiversity, and diversifying rural livelihoods (Lu & Li 2006; Xie et al 2011; Freed et al 2020; Wan et al 2019; Frei & Becker 2005; Ge et al 2023). Conservation initiatives around GIAHS sites such as Qingtian and the broader promotion of integrated rice field aquaculture in China built explicitly on the long historical continuity of rice–fish co-culture, positioning it as both a cultural heritage and a contemporary pathway for resilient, resource efficient agriculture in the face of global environmental change (Lu & Li 2006; Xie et al 2011; Freed et al 2020; Yuan et al 2022; Ge et al 2023; Halwart & Gupta 2004; Ye et al 2022; Ren et al 2018) (Table 1).

Table 1

Historical contexts shaping rice–fish co-culture

<i>Period / context</i>	<i>Key historical features of rice–fish co-culture</i>	<i>References</i>
Early Neolithic Yangtze wetlands	Co-evolution of wetland rice use and fish exploitation by Austroasiatic communities; transition from hunting–gathering–fishing to mixed farming that underpinned later integrated rice–fish systems	Edwards 2025
Classical and imperial China	Emergence of documented pond fish culture (Shang oracle bones); Fan Li’s carp-farming treatise; policy-driven shifts in carp species during Tang dynasty; spread of deliberate rice–fish co-culture over ~1700 years	Edwards 2025; Lu & Li 2006; Halwart & Gupta 2004
Medieval to early modern south China	Consolidation of long-lived terraced rice–fish systems such as Qingtian (ca. 1200 years); development of specialized local rice and carp landraces; increasing symbolic and cultural value	Lu & Li 2006; Xie et al 2011; Li et al 2025; Ren et al 2018
Twentieth century to present	Co-culture recast as sustainable intensification strategy; recognition as GIAHS; expansion of integrated rice field aquaculture research and policy, with parallel traditional systems documented across South and Southeast Asia and beyond	Lu & Li 2006; Xie et al 2011; Freed et al 2020; Yuan et al 2022; Frei & Becker 2005; Ge et al 2023; Halwart & Gupta 2004.

Yield and Production Performance of Rice-Fish Co-Culture. Rice yields in well designed rice–fish systems are typically maintained or increased relative to rice monoculture, while adding substantial aquatic animal yield. In long term Chinese systems, rice yield in co-culture matched monoculture when fish yields stayed below system specific thresholds, and fish yields could be “substantially higher” than in traditional systems with no rice yield loss (Hu et al 2016). In heritage systems, rice yield and yield stability are similar to monoculture, despite a 68% reduction in pesticides and 24% less fertilizer (Xie et al 2011).

In Thailand, rice–fish farms showed about 16% higher rice yield when freshwater fish or prawns were stocked, with survival above 80% (Kaewpuangdee et al 2024). Recent US work indicates koi carp can be grown with sushi rice while enhancing rice yield, milling yield, and grain protein and generating positive net returns from koi (Jia et al 2025).

Rice–crayfish co-culture often maintains or slightly increases rice yield (up to 5–7% above monoculture) while delivering significant crayfish output (Hou et al 2021; Hou et al 2020; Li et al 2024b). In tropical China, annual rice–crayfish production equaled monoculture rice despite a one third reduction in N fertilizer (Li et al 2024b) (Table 2).

Table 2

Illustrative yield and profitability outcomes in rice–fish systems

<i>System type and context</i>	<i>Rice yield effect vs. monoculture</i>	<i>Aquatic animal / other output</i>	<i>Economic effect</i>	<i>References</i>
Traditional rice–fish (China, heritage)	Similar yield and stability	Fish for food	68% less pesticide, 24% less fertilizer, no yield loss	Xie et al 2011
Intensive rice–fish (China)	No reduction below fish–yield thresholds	High fish yield achievable	Higher net income than rice monoculture	Hu et al 2016
Rice–crayfish (Jiangnan Plain, China)	–30–55% vs. rice–rapeseed on deep groundwater; ~similar to monoculture on shallow groundwater	Crayfish as protein source; feed can raise yield 31–71%	Profitability maintained or increased, depending on groundwater and feed	Hou et al 2020
Rice–crayfish (Jingzhou, China)	+5–7% vs. rice monoculture	Higher crayfish yield in co-culture vs rotation	Value-to-cost and benefit-cost ratios increased strongly	Hou et al 2021
Tropical rice–crayfish (Hainan, China)	Annual production equivalent with 33% less N	Crayfish as additional product	Net profit +153–745% vs. monoculture, variety-dependent	Li et al 2024b
Rice–fish/prawn (Thailand)	Rice yield \approx +16%	Multiple fish species or prawn; >80% survival	Co-culture framed as “nature-based solution” for productivity	Kaewpuangdee et al 2024
Rice–fish (Thailand, ecosystem service valuation)	Not highlighted as higher yield, but co-culture more valuable in net ecosystem services	Multi-species fish	Average economic value +25.4% vs. monoculture	Arunrat & Sereenonchai, 2022
Koi carp–rice (USA)	Enhanced rice yield, milling yield, protein	Ornamental koi	Positive estimated net returns from koi	Jia et al 2025
Pond rice–fish (China)	Rice added to fish ponds	Rice as new crop; fish maintained	Net income +114% vs. fish monoculture with only 2.9% higher cost	Jin-Fei et al 2016.

Ecological and Agronomic Advantages. A consistent benefit is ecological intensification: more output per unit of land and input, with ecosystem services substituted for chemicals. Fish significantly reduce insect herbivores (by ~24%) and weeds (up to ~60–70% reduction in abundance, richness, and biomass), increase predatory arthropods (~19%), and cut pesticide use by ~23–68% in various Chinese systems (Wan et al 2019; Xie et al 2011; Li et al 2024a; Berg & Tam 2018). This supports higher or stable rice yields with lower chemical input (Wan et al 2019; Li et al 2024a; Hu et al 2016; Xie et al 2011; Nayak et al 2018; Mariyono 2023). Plants sometimes contribute to the decontamination of water from various natural or artificial toxic compounds (Tumembouw et al 2024; Petrescu-Mag & Gavrioloaie 2019).

Soil quality improves through higher organic matter, nitrogen, phosphorus, and potassium, as shown in heritage rice–fish systems, rice–crayfish systems, and integrated fish–rice–duck systems (Wan et al 2019; Hou et al 2020; Li et al 2024ab; Kaewpuangdee et al 2024; Liu et al 2023; Nayak et al 2018; Wang et al 2022). Earthworms and benthic fauna increase under co-culture, enhancing nutrient cycling and soil structure (Li et al 2024ab; Nayak et al 2018). Water quality benefits include reduced N and P in aquaculture ponds when rice is added (total N and P in water reduced by ~55–85%) and strong removal of nitrogen forms as pond water flows through rice fields (Kaewpuangdee et al 2024; Liu et al 2023; Jin-Fei et al 2016).

Ecosystem service valuations in Thailand showed higher total economic value of regulating and supporting services (temperature and humidity regulation, biodiversity, agrotourism potential) in rice–fish versus monoculture (Arunrat & Sereenonchai 2022).

Socio economically, many studies report higher farm profitability due to added fish/crayfish outputs, reduced fertilizer and pesticide expenditures, and sometimes lower irrigation demand (Wan et al 2019; Hou et al 2020; Arunrat & Sereenonchai 2022; Hu et al 2016; Hou et al 2021; Li et al 2024ab; Jin-Fei et al 2016; Mariyono 2023). Co-culture can diversify income (e.g., crayfish, prawns, ornamental koi, agrotourism) and has been socially acceptable in Indonesian villages without conflicts with norms or government (Mariyono 2023).

Disadvantages, Constraints, and Risks. Despite advantages, rice–fish systems are not universally beneficial. Rice–crayfish systems in the Jiangnan Plain reduced sustainability indices relative to rice monoculture: renewable fraction, emergy yield ratio, and emergy sustainability index decreased, while environmental loading increased by 18–23%, driven by labor and service inputs, fertilizer use, and machinery (Hou et al 2021). A review of rice–animal co-culture notes risks of water quality deterioration and lower profitability when animal stocking densities and feed inputs are too high or field conditions unsuitable (Bashir et al 2020).

Hydrological context is critical in both poly- or monoculture (Pandey & Tiwari 2012). In deep groundwater areas, rice–crayfish co-culture had 30–55% lower rice yield than rice–rapeseed rotations, even while reducing CH₄ emissions and pesticides (Hou et al 2020). In Ziro Valley (India), a field survey found current rice–fish practices yield poor economic returns due to mismanaged inputs, limited willingness to invest, lack of funds and training, and low youth engagement; improving stocking density, manuring and farmer training were identified as priorities (Samaddar et al 2024).

From a pest management perspective, heavy pesticide use or parallel anthropic activities can undermine co-culture performance as fish are sensitive to various chemicals (Petrescu-Mag & Petrescu-Mag 2010; Petrescu-Mag et al 2010, 2011, 2013; Agusnimar et al 2025; Hasibuan et al 2025). In the Mekong Delta, rice–fish farmers with high pesticide use had lower fish survival, lower fish and rice yields, and lower income compared with low pesticide rice–fish farmers; pesticide related health problems were common among all groups (Berg & Tam 2018).

Adoption barriers include farmers' concerns over drought risk, lack of science based extension services, technical complexity (field configuration, species and variety choice, lodging resistance), and capital or knowledge constraints (Hu et al 2016; Samaddar et al 2024; Bashir et al 2020; Li et al 2023; Mariyono 2023). Rice varieties differ widely in

lodging resistance and yield under co-culture; careful selection is required to achieve 7–13 t ha⁻¹ annual grain yields while supporting fish (Li et al 2023).

Types of Rice–Fish and Related Co-Culture Systems. Research covers a spectrum of configurations. Traditional in situ paddy co-culture with carp or other fish has been practiced for over 1,200–2,000 years and is recognized as an agricultural heritage system in China (Hu et al 2016; Xie et al 2011). Variants include rice–crayfish rotation and co-culture using ditches that occupy ~10% of the paddy area, with rice on the remaining area (Hou et al 2020; Hou et al 2021; Li et al 2024ab). Rice–prawn and multi species fish–rice systems in Thailand show species specific effects on yield and water/soil properties (Arunrat & Sereenonchai 2022; Kaewpuangdee et al 2024).

Aquaponic systems and rice–fish co-culture systems have inspired each other (Lesmana et al 2024; Ulfah & Dewi 2025; Setijaningsih et al 2025). Novel rice–fish systems include ex situ rice–fish, where fish ponds and rice paddies are hydraulically linked; pond water rich in nutrients is polished by rice, reducing TN, TP, and other pollutants by ~45–73% and enriching beneficial nutrient transforming bacteria (Liu et al 2023). Another innovation is integrating rice into intensive fish ponds to remove nutrients and add rice output (Jin-Fei et al 2016).

Rice can also be combined with additional components such as ducks, forming rice–fish–duck systems that further enhance nutrient recycling, biological diversity, and profitability compared with conventional rice (Nayak et al 2018). Finally, ecosystem based concepts like wild rice–fish integration have been proposed for new regions, emphasizing potential ecological and nutritional benefits, though they remain largely theoretical at present (Ahmed et al 2020).

Mechanistic Interactions Between Rice and Aquatic Organisms. Rice–fish co-culture systems are structured around a complex network of biological interactions that operate across multiple trophic and functional levels. At the core of these systems lies a reciprocal relationship between the rice plants and the aquatic organisms, mediated by both direct and indirect ecological processes. Fish actively forage within the flooded paddy environment, consuming insect herbivores, larvae, and various invertebrates that would otherwise impose biotic stress on rice plants. This trophic regulation extends beyond simple predator–prey dynamics (Petrescu-Mag 2025), as the selective feeding behavior of fish can reshape community composition, favouring beneficial arthropods and reducing pest outbreaks through both consumptive and non-consumptive effects (Mustikasari et al 2025).

Simultaneously, fish movement within the water column and sediment interface contributes to continuous bioturbation. This mechanical disturbance enhances the resuspension of nutrients and prevents stratification in the shallow aquatic layer, thereby increasing nutrient availability for rice roots. The disturbance of the soil surface also inhibits the establishment of certain weed species, either by uprooting seedlings or by altering microhabitat conditions required for germination. These interactions exemplify how physical ecosystem engineering by aquatic organisms can translate into agronomic benefits.

The physiological interface between rice plants and aquatic organisms is further mediated through excretory processes. Fish release nitrogenous wastes, primarily in the form of ammonia, directly into the water (Dewi et al 2024). This readily available nitrogen can be assimilated by rice plants either through the root system or via associated microbial communities in the rhizosphere. The rhizosphere itself becomes a dynamic zone of interaction, where plant root exudates stimulate microbial growth, and microbial transformations regulate nutrient availability (Wankhade et al 2025; Pantigoso et al 2022; Grayston et al 1997; Schmautz et al 2017; Gong et al 2023; Hartmann et al 2009; Adeniji et al 2024; Joyce et al 2019). The presence of fish has been shown to influence microbial community structure, promoting taxa involved in nitrification, denitrification, and organic matter decomposition (Ruiz et al 2026; Rogge et al 2024; Yang et al 2024; Lo et al 2022; Zeng et al 2025; Yamane et al 2021; Schmautz et al 2017; Choi et al 2025; Fan et al 2025).

Oxygen dynamics represent another critical axis of interaction (Du & Li 2026). Rice plants, through aerenchyma tissues, transport oxygen from the atmosphere to the root zone, partially oxygenating otherwise anoxic sediments. This localized oxygenation can mitigate the accumulation of toxic reduced compounds such as hydrogen sulfide, thereby improving conditions for both plant roots and benthic organisms. In turn, the activity of aquatic fauna influences oxygen demand and distribution within the system, creating a tightly coupled feedback loop between plant physiology and aquatic metabolism.

These mechanistic interactions collectively illustrate that rice–fish systems function not merely as co-located species assemblages, but as integrated ecological units in which biological, chemical, and physical processes are deeply intertwined. The productivity and stability of the system emerge from these interactions rather than from isolated contributions of individual components.

Biogeochemical Cycling and Nutrient Dynamics. The functioning of rice–fish co-culture systems is fundamentally governed by the circulation and transformation of nutrients across interconnected compartments, including water, soil, biota, and the atmosphere. These systems operate as semi-closed biogeochemical units in which internal recycling processes can partially substitute for external inputs, thereby enhancing resource-use efficiency.

Nitrogen dynamics are particularly central to system performance. In conventional rice monocultures, nitrogen inputs are often dominated by synthetic fertilizers, with significant losses through leaching, volatilization, and denitrification (Chandra et al 2025). In contrast, rice–fish systems introduce additional nitrogen pathways through fish excretion and the decomposition of organic matter derived from feed residues, plankton, and detritus. Ammonium released by fish is rapidly incorporated into the microbial loop or directly taken up by rice plants. The presence of diverse microbial communities facilitates the transformation of nitrogen between its various forms, including ammonification, nitrification, and denitrification, thereby regulating its availability and mobility.

Phosphorus cycling follows a similarly dynamic pattern, although it is more strongly influenced by sediment interactions. Fish activity enhances the mobilization of phosphorus from sediments into the water column, increasing its bioavailability. At the same time, plant uptake and microbial immobilization act as sinks, preventing excessive accumulation in the water. The balance between these processes determines whether the system functions as a net source or sink of phosphorus, with implications for both productivity and environmental impact (Wang et al 2025b; Yaobin et al 2019; Mok et al 2021).

Carbon dynamics in rice–fish systems are closely linked to both primary production and decomposition processes. Rice plants contribute organic carbon through root exudates and plant residues, while aquatic organisms contribute through metabolic waste and biomass turnover. Microbial decomposition of organic matter drives the release of carbon dioxide and, under anaerobic conditions, methane. The introduction of fish can alter these pathways by modifying sediment conditions and influencing microbial community composition. In some cases, bioturbation and improved oxygen penetration can suppress methanogenesis, while in others, increased organic inputs may stimulate it, depending on system management (Hou et al 2025; Duan et al 2025; Zhao et al 2023; Wang et al 2025a; Zhu et al 2023; Xu et al 2023).

Water serves as the primary medium for nutrient transport, linking spatially distinct processes within the system. The continuous exchange between water and soil compartments allows for the redistribution of nutrients, while hydrological management practices, such as controlled flooding and drainage, further regulate nutrient fluxes. In integrated systems where water is recirculated between ponds and paddies, nutrient gradients can be deliberately exploited to enhance purification processes, with rice fields acting as biofilters that remove excess nitrogen and phosphorus from aquaculture effluents (Yaobin et al 2019; Wu et al 2022; Wang et al 2024a; An et al 2025; Yang et al 2017; Herlambang et al 2021; Zhang et al 2023ab; Gao et al 2025).

The integration of biological components thus transforms the rice field into a multifunctional biogeochemical reactor. Nutrient losses are reduced, internal cycling is intensified, and the system gains a degree of autonomy from external inputs. However, the efficiency of these processes is highly sensitive to management variables, including stocking density, feeding regimes, water depth, and soil characteristics, all of which influence the balance between nutrient retention and loss.

Climate Change Resilience and Adaptation Potential. Rice–fish co-culture systems have been increasingly examined through the lens of climate change, particularly in relation to their capacity to enhance resilience and adaptive potential in agricultural landscapes (Freed et al 2020; Ahmed et al 2014; Bashir et al 2020; Arunrat & Sereenonchai 2022). These systems exhibit a range of structural and functional attributes that can buffer environmental variability and mitigate some of the adverse effects associated with changing climatic conditions (Freed et al 2020; Bashir et al 2020; He et al 2023; Arunrat & Sereenonchai 2022) (Figure 1).

One of the key aspects of resilience lies in the hydrological flexibility of rice–fish systems. The presence of standing water in paddy fields provides a buffering capacity against short-term drought events by maintaining soil moisture and reducing temperature fluctuations at the root level (Bashir et al 2020; He et al 2023; Arunrat & Sereenonchai 2022). At the same time, the integration of aquatic organisms necessitates more careful water management, which can encourage the development of irrigation practices that are both more efficient and more adaptive to variable water availability (Freed et al 2020; Bashir et al 2020; He et al 2023; Arunrat & Sereenonchai 2022). In flood-prone regions, the coexistence of rice and fish can also offer advantages, as fish are inherently adapted to aquatic conditions and can utilize temporary inundation periods that might otherwise damage terrestrial crops (Freed et al 2020; Ahmed et al 2014; Bashir et al 2020; Poelma et al 2021).

Thermal regulation is another important dimension. Water has a high heat capacity, which allows it to moderate temperature extremes within the paddy ecosystem (He et al 2023; Arunrat & Sereenonchai 2022). This can reduce heat stress on rice plants during periods of elevated air temperature and create a more stable microclimate (He et al 2023; Arunrat & Sereenonchai 2022). Aquatic organisms, in turn, may be sensitive to temperature fluctuations, but the buffered environment of the rice field can provide refuge compared to more exposed aquatic systems (Bashir et al 2020; Arunrat & Sereenonchai 2022).

From a productivity standpoint, diversification is a central mechanism of adaptation (Freed et al 2020; Bashir et al 2020; Bhattacharya 2024; He et al 2023; Hu et al 2016; Wang et al 2024c). By producing both plant and animal biomass within the same system, farmers reduce their dependence on a single crop and thereby spread risk (Freed et al 2020; Bashir et al 2020; Bhattacharya 2024; Hu et al 2016; Wang et al 2024c). Climate-induced crop failures may be partially offset by aquatic production, and vice versa, depending on the nature of the disturbance (Freed et al 2020; Bashir et al 2020; Hu et al 2016; Poelma et al 2021; Wang et al 2024c). This diversification extends beyond yield to include income streams, dietary diversity, and livelihood strategies, all of which contribute to socio-ecological resilience (Freed et al 2020; Ahmed et al 2014; Bhattacharya 2024; He et al 2023; Hu et al 2016; Poelma et al 2021; Wang et al 2024c).

Rice–fish systems also interact with greenhouse gas dynamics (Wang et al 2025a) in ways that are relevant to climate mitigation and adaptation (Petrescu-Mag et al 2022, 2023; Oroian et al 2023). Flooded rice fields are a known source of methane emissions due to anaerobic decomposition processes. The introduction of fish can modify sediment conditions and organic matter distribution, potentially influencing methane production and emission pathways (Frei & Becker 2025; Datta et al 2009; Bhattacharyya et al 2013). In some configurations, increased oxygenation and altered microbial communities may reduce methane emissions, while in others, higher organic inputs could enhance them. Nitrous oxide emissions are likewise influenced by nitrogen cycling processes, which are modified by the presence of aquatic organisms and associated microbial activity (Wang et al 2024b).

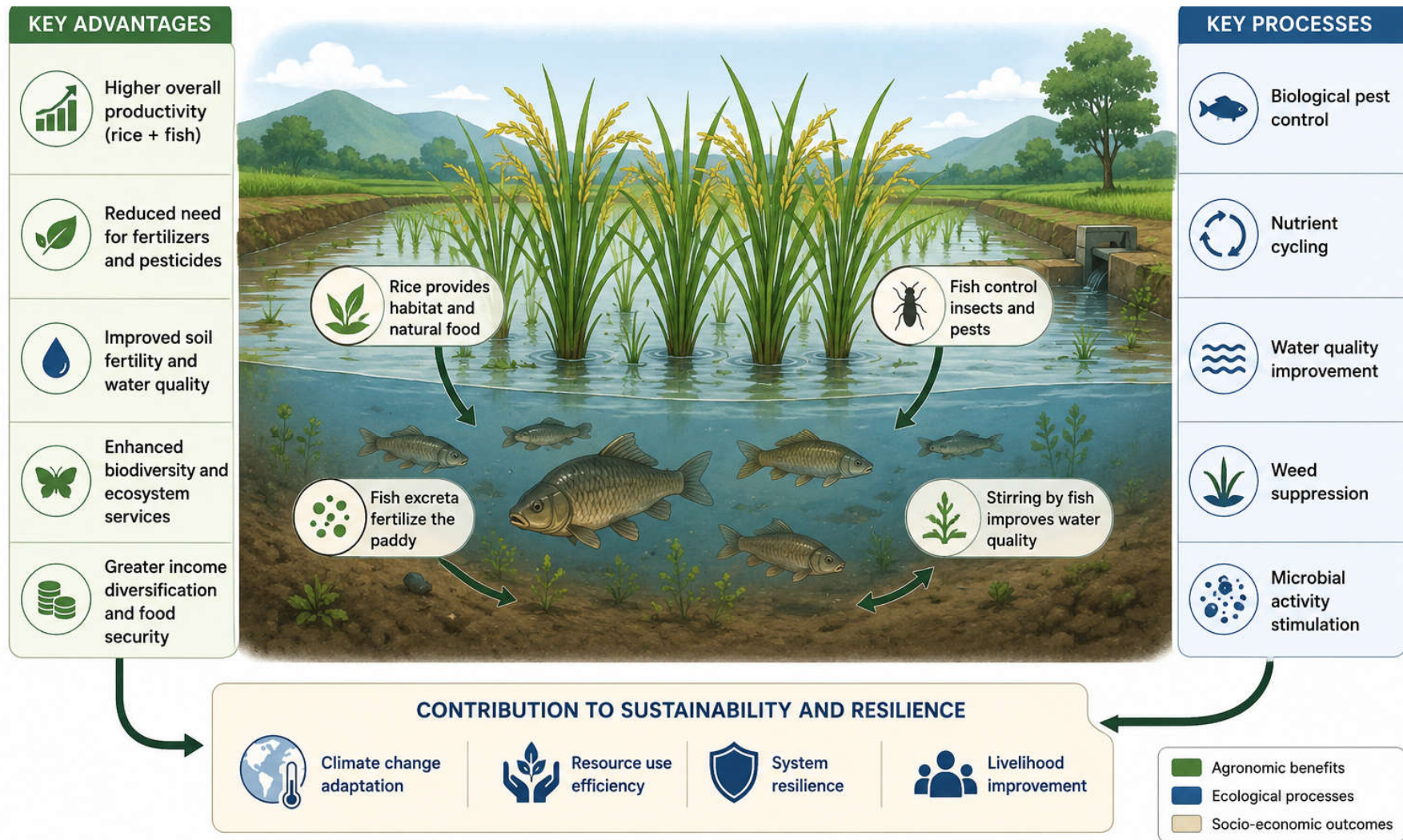


Figure 1. Rice-fish co-culture system: integrated production for food security, ecosystem health and resilience.

Adaptation potential is further shaped by the knowledge systems associated with rice–fish co-culture. Many of these systems are rooted in long-standing traditional practices that have evolved under variable environmental conditions. This accumulated ecological knowledge can provide a foundation for adaptive management, enabling farmers to adjust stocking densities, species combinations, and water regimes in response to climatic signals. At the same time, the integration of modern technologies and scientific insights can enhance this adaptive capacity, particularly in regions where climate change is expected to impose novel or intensified stresses.

The resilience of rice–fish systems is therefore not a static property but an emergent characteristic arising from the interaction of ecological processes, management practices, and socio-economic context (Bordea & Popescu 2023; Petrescu-Mag 2026).

Conclusions. Rice–fish co-culture systems exemplify a multifunctional approach to agricultural production, integrating biological, chemical, and physical processes into a cohesive and efficient agroecosystem. The evidence reviewed demonstrates that these systems can achieve comparable or enhanced rice yields relative to monoculture while simultaneously generating additional aquatic biomass, thereby improving overall productivity and economic returns. Their ecological advantages are substantial, including reduced dependence on agrochemicals, improved soil and water quality, enhanced biodiversity, and strengthened ecosystem services.

At a mechanistic level, the success of rice–fish systems arises from complex interactions between rice plants, aquatic organisms, and microbial communities, which collectively regulate nutrient cycling and ecosystem functioning. These interactions transform the rice field into a semi-closed biogeochemical system with increased internal resource efficiency. Moreover, the diversification inherent in rice–fish co-culture enhances resilience to environmental variability and climate change, providing both ecological stability and socio-economic security.

However, the performance of these systems is highly context-dependent. Factors such as hydrological conditions, stocking density, species selection, and management practices critically influence outcomes. Inadequate technical knowledge, economic constraints, and institutional barriers can further limit adoption and effectiveness. In some cases, intensification without proper management may lead to environmental trade-offs or reduced sustainability.

Overall, rice–fish co-culture represents a viable pathway toward sustainable agricultural intensification, but its successful implementation requires site-specific optimization, improved extension services, and continued interdisciplinary research. Future efforts should focus on refining management practices, enhancing system adaptability, and integrating traditional knowledge with modern scientific approaches to maximize both productivity and sustainability.

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