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REVIEW

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Rice-aquatic animal co-culture impacts on agroecological, environmental and socioeconomic sustainability

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ABSTRACT

Rice (*Oryza sativa* L.) significantly contributes to greenhouse gas (GHGs) emissions and environmental nitrogen losses. Carbon dioxide emissions reach 36.8 billion tons annually, while methane emissions total 580 million tons per year, with 60% from human activities. Rice serves as a fundamental food source for 3 billion individuals. Innovative and sustainable management of rice fields is necessary to increase yields. This review explores the potential benefits and limitations of rice-animal co-culture (CRA). It addresses key questions about the impact of co-culture on farm profitability, water quality, and GHGs, highlighting its ecological, economic, and social advantages such as increased farm productivity, improved resource utilization, enhanced biodiversity, and reduced GHGs. However, barriers to adoption include a lack of extension programs and farmer's concerns about drought risks. Misuse of the system, such as unbalanced nutrient application can degrade water quality and reduce profitability. Further research on the effects of CRA under different climates and on-field conditions is essential, and extension programs that require policy and technical support from public and private organizations are required to promote widespread adoption.

KEYWORDS

Rice-animal co-culture; Agricultural sustainability; Environmental sustainability; Ecological sustainability; Socioeconomic sustainability; Greenhouse gas

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Introduction

Population growth has led to global challenges such as food shortages, nutrient deficiency, less water and land resources availability for agriculture and environmental degradation [1,2]. Rice (*Oryza sativa L.*) serves as a staple food and its production covers 155 to 160 million hectares (ha) and feeds 50% of the worldwide population plays a key role in meeting global food security needs [3]. Each year, about 480 million tons of milled rice are produced [4], with China and India alone accounting for 50% of rice cultivation and consumption [5]. Economically, rice is an important agricultural commodity, affecting the livelihoods of millions of farmers and an integral part of the agri-food system [6]. In 2022, China's rice output will exceed 208 million tons and becoming the world's largest rice cultivator. Ensuring sustainable rice production while addressing challenges such as climate change, resource scarcity and market volatility is critical to maintaining food security and economic stability. But it is a major sector that wastes water and emits greenhouse gases (GHGs) [7].

Aquatic foods, including fish and other marine life are critical to global food security. It is providing essential nutrients to billions of people around the world [8]. Since 1961, world consumption of aquatic food has increased by an average annual rate of 3.0% and reached 20.2 kilograms per capita which is more than twice the consumption in the 1960s [9,10]. In 2021, approximately 23.8 million tons of aquatic food were lost or wasted, accounting for 14.8% of global production [11]. Co-culture of rice and aquatic animals (CRA) is a strategy to enhance land and water resource utilization and reduce environmental pollution [12]. This review explores the advantages and limitations of CRA with focusing on its impact on farm profitability for environmental and management of rice production systems sustainability [13]. Specifically, it examines the effects of CRA on water quality, food yields, greenhouse gas emissions, and nitrogen (N) transformations. Rice production consumes 90% of Asia's irrigation water and makes it a significant source of resource waste and greenhouse gas emissions [14].

Rice cultivation requires huge application of chemical fertilizers that can have adverse environmental impacts such as N loss GHGs emissions and water pollution [15]. N is a macronutrient that contributes to high crop yields and is used in 16% of fertilizers used in rice systems globally [12]. Only 28% is used by rice crops and the rest of fertilizer results in runoff, leaching, gas emissions, and soil retention [16]. Aquaculture is the cultivation of aquatic organisms such as fish, shellfish, crabs, and shrimp in marine or freshwater systems which is a key component of food security. Rice fields contain large amounts of water that can be used for aquaculture such as CRA farming. The system can provide sufficient numbers of aquatic animals for food and control problems associated with monoculture aquaculture systems through the complementary use of water and land resources.

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Co-culture systems have the potential to enhance food security and improve farmer economies in rural areas, as they provide more external feed containing nutrients and minimize environmental pollution [17,18].

Ancient China and India initiated the practice of CRA with the practice being developed in China around 2000 years ago. It has since been adopted by countries such as Vietnam, India, Indonesia, Malaysia, Egypt, Philippines and Bangladesh [19,20]. In recent decades, CRA has gained attention because of its economic returns with surety. Additional aquatic species have appeared in co-culture systems, including shrimps, crabs, crayfish, prawns, turtles and duck. The softshell turtle has been increasingly integrated into CRA in China due to its extensive medicinal applications, high protein content, and significant economic value. Objectives of the study are to evaluate the feasibility and positive aspects of CRA in addressing global food security challenges, resource efficiency, and environmental sustainability while assessing their impact on farm profitability, water quality, and greenhouse gas emissions [21,22].

Agricultural Sustainability

China leads in efficiently using co-culture systems and optimizing resources to achieve high output of rice and aquatic life. As early as 1990, China's aquatic animal output from 740,000 ha of rice fields was only 130,000 tons. Fast forward to 2020 and those numbers have ballooned from 2.56 million ha to 3.25 million tons. It's not just about quantity; Rice yields are consistently 8.7% to 12.1% higher on these water-rich lands [23]. Fish, crabs and turtles thrive in the rice fields, playing their part in fending off pests and promoting nutrient recycling [24]. It's a win-win for the rice and the people who live in the water. A research showed that China's fish production is relatively high, approximately 1.9 to 2.5 t ha^{-1}, followed by Vietnam 2.2 t ha^{-1}, India 1.3 to 2.0 t ha^{-1}, Bangladesh 1.08 t ha^{-1}, Indonesia 0.3 to 0.89 t ha^{-1} and Thailand 0.9 to 1.1 t ha^{-1} with rice yield of 9.3 to 12 t ha^{-1}, 4.2 to 5.7 t ha^{-1}, 3.0 to 4.6 t ha^{-1}, 3.8 to 5.0 t ha^{-1} and 6.5 to 7.8 t ha^{-1} respectively whereas, the co-culture with rice were crayfish, turtle, fish and crabs in China, fish in Indonesia, Vietnam and Thailand, crabs, shrimps, and fish in India and prawn, shrimps and fish in Bangladesh. Common fish species were used in this study were *Barbodes gonionotus, Oreochromis niloticus, Cirrhinus mrigala, Puntius gonionotus, Catla catla* and *Cyprinus carpio* [12]. Because of beneficial results, India and Indonesia have launched extension plans for farmers to shift their traditional rice cultivation system to rice and aquatic animals co-culture system. CRA has become an important aspect of India's organic aquaculture program. Inspired by its success and effectiveness in Asian countries, African countries have adopted similar co-cultural systems [25].

Environmental Interactions

Rice cultivation faces challenges from abiotic and biotic stresses, affecting yield and quality. Biological challenges include bacterial leaf blight, rice blast and bakanae disease. Weeds also compete for resources and hinder productivity. Abiotic stresses in agriculture pose major challenges to crop growth. Drought and high temperatures can reduce yields, while flooding and high soil salinity can hinder water and nutrient uptake. Harmful radiation and gaseous pollutants such as ozone also impair photosynthesis. Heavy metals in contaminated soil further threaten crop growth. The impact of these pressures is staggering [26]. Modeling studies show that by 2050, average rice yields could be 17% lower than in 2000. This could lead to food insecurity for an estimated 1.6 billion people in Asia and malnutrition for millions of children in South and East Asia [27].

Environmental factors influencing CRA include water level, temperature, transparency, pH, dissolved oxygen, and carbon dioxide (DOC). Levels of DOC depend mainly on the photosynthesis of organisms and the respiration species in CRA. Elevated CO_2 and NH_3 concentrations pose significant risks to farmed animals [25,28]. Rice cultivation considered as source of pollutant for water bodies because of nutrients and pesticide application. Improvement of paddy water in important of rice cultivation. Rice mono-cultivation utilize only the required N and rest is lost on environment [12]. On other hands, rice-aquatic life co-culture trend enhances N use efficiency for plants and reduce its losses because of aquatic life. By improving the organic carbon, P, N, and K this so-culture enhance soil fertility and production sustainability. Previous researches reported that this co-culture reduces the fertilizers use up-to 26% as compare to mono-cultured rice farming. Moreover, reduced nutrients (N and P) concentration in co-culture was reduced up-to 79% than mono-cultured fish farming. Co-culture system minimized the pesticide use up-to 68% [12,29,30].

Recommended conditions (Figure 1) for CRA are designed to support the growth and health of rice (culture period of 90-120 days) and aquatic organisms. Keeping carbon dioxide levels below 10 ppm prevents acidic conditions, while dissolved oxygen levels between 5.0-7.5 ppm ensure adequate respiration for aquatic life. A water level of 30-90 cm provides optimal submergence space for rice and optimal habitat space for aquatic organisms with a pH range (neutral to alkaline) from 6.5 to 9.0 supports nutrient availability and safety for plants and animals. Water clarity of 25-30 cm provides sufficient light for photosynthesis while maintaining a healthy ecosystem balance, and a temperature range of 25-35°C, and ionized ammonia promotes optimal growth and development of rice and tropical aquatic life [28]. Designs recommendations provided by various researches are rice ridge and fish ditch farming system in China, peripheral trench, latticed trenches, Y-shaped trench, diagonal trench, peripheral with one central longitudinal trench, peripheral with two equidistant transverse trenches and design and construction of Indonesian rice + fish farm with lateral pond [19,31,32].

CO2 <10 ppm	**Optimum Conditions for Co-culture**	Water pH 6.5-9.0
Dissolved O2 5.0-7.5 ppm		Water Transparency 25-30 cm
Water Level 30-90 cm		Water Temperature 25-35°C

CO_2: Carbon dioxide; O_2: Oxygen; °C: Degree Celsius; cm: Centimeter; ppm: Parts per million

Figure 1. Optimum conditions required for co-culture of rice and aquatic organisms.

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A study conducted to evaluate the viability and economic impact of an integrated CRA in Bangladesh found that this approach provides greater net positive aspects and lower production costs for fish and rice than rice monoculture because yields were higher. Compared to rice monoculture net farm income in co-farming systems was 64.4% more in the wet season and 98.2% more in the dry season. Furthermore, fish production increases by 600 kg ha per year in shallow inundated regions and by 1.5 t ha_{-1} in deeply inundated regions. Co-culture systems generated US 437 ha_{-1}, 20-85% higher than monocultures [29,33].

Agricultural sector is the main source of GHGs and mainly emits methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O). In CRA, aquatic animals increase dissolved oxygen (DO) levels through their movement in the water, potentially reducing greenhouse gas emissions [34]. Anthropogenic activities in rice systems participate approximately 20% of world's CH_4 production [35]. Methane emissions from these systems depend on the anaerobic degradation of organic matter in underwater conditions with a low oxygen supply. Aquatic animals such as crabs and carp can affect CH_4 production by affecting soil layers and increasing DOC in water and soil. A meta-analysis of 247 pairwise comparisons demonstrated that CRA significantly alleviated CH_4 emission by 86.8% and also improved rice output by 49.2% in Table 1.

Table 1. Current commercially available ultrasound contrast agents.

Category	Details
Advancements in Rice-Aquatic Animal Co-Culture	
Increased Rice Yield	Rice-animal co-cultures boost rice yield compared to rice monocultures.
Soil Health Enhancement	Increases soil organic carbon and total nitrogen content, contributing to soil fertility.
Reduced Pesticide and Fertilizer Use	Requires less pesticide and fertilizer application.
Nitrogen Runoff Reduction	Decreases nitrogen runoff by 16% compared to monocultures.
Leaching Reduction Creating Synergistic Ecosystem	Reduces leaching by 13% in rice-animal co-culture systems.
Increased Annual Rice Yields	Increases annual rice yields by 4% (global assessment of 155 case studies).
Methane Emissions Alleviation	Reduces CH_4 (methane) emissions by 86.8%.
Significant Rice Yield Improvement	Improves rice yield by 49.2%.
N_2O Emissions Impact	No significant effects on N_2O (nitrous oxide) emissions relative to rice monocultures.
Future Focus	
Trait Matching	Identifying traits in aquatic animals and rice varieties that create productive and sustainable co-culture partnerships.
Culturing Strategies	Developing compatible culturing strategies for successful co-culture implementation.

CRA has been found to reduce methane emissions and the potential for global warming. CRA was observed to decrease the global warming potential by 12.9% and GHGs intensity 4.9% [39]. Additionally, CRA emphasizes the influence of microbial behavior, drainage, and has no significant effects on N_2O emission relative to rice monoculture. Conversion from traditional rice monoculture to CRA involving fish, crab, crayfish, and duck has been shown to significantly reduce N_2O emissions and improve N use efficiency. CRA offer many positive aspects to farmers and others including ecological, economic and social advantages. CRA can improve field water ecology, increase sources of organic fertilizer, and change the carbon-nitrogen ratio. But it may also lead to resource competition and water pollution downstream [33,34].

Ecological Benefits

CRA provide a variety of benefits to farmers and others, including ecological, economic, and social advantages. CRA improves field water ecology, provide organic fertilizer, and thereby increase the carbon-nitrogen ratio [22]. However, there are concerns about possible water contamination from aquatic animal waste and excess feed [40]. The ecological positive aspects of CRA are mainly related to resource and nutrient utilization and biodiversity (Figure 2). Biodiversity is threatened by environmental pressures and human activities in aquatic ecosystems. CRA maintain biodiversity and support a variety of aquatic flora and fauna. Researches show that these co-culture systems have no negative impact on fish abundance and aquatic biodiversity [39,40]. The adoption of CRA can enhance biodiversity and enable resilient and productive agriculture. CRA is a complex integrated system with direct and indirect interactions between organisms. The system improves water utilization efficiency by providing shade, soil loosening, and pest control for aquatic animals. Year-round flooding conditions can reduce soil fertility and alter soil properties [21].

Co-culture also promotes a dynamic nutrient cycle. Excess N in the rice fields is absorbed by aquatic animals and their excrement becomes nutrients for the rice plants and utilizing excess N for fish production can help improve the socioeconomic status of rural communities [20]. CRA has gained global attention since the 1970s with many governments promoting the adoption of this technology through technical support and tax incentives. With the world's largest cultivated land area, China encourages farmers to shift to intensive CRA to enhance agricultural productivity. These enhanced co-culture systems not

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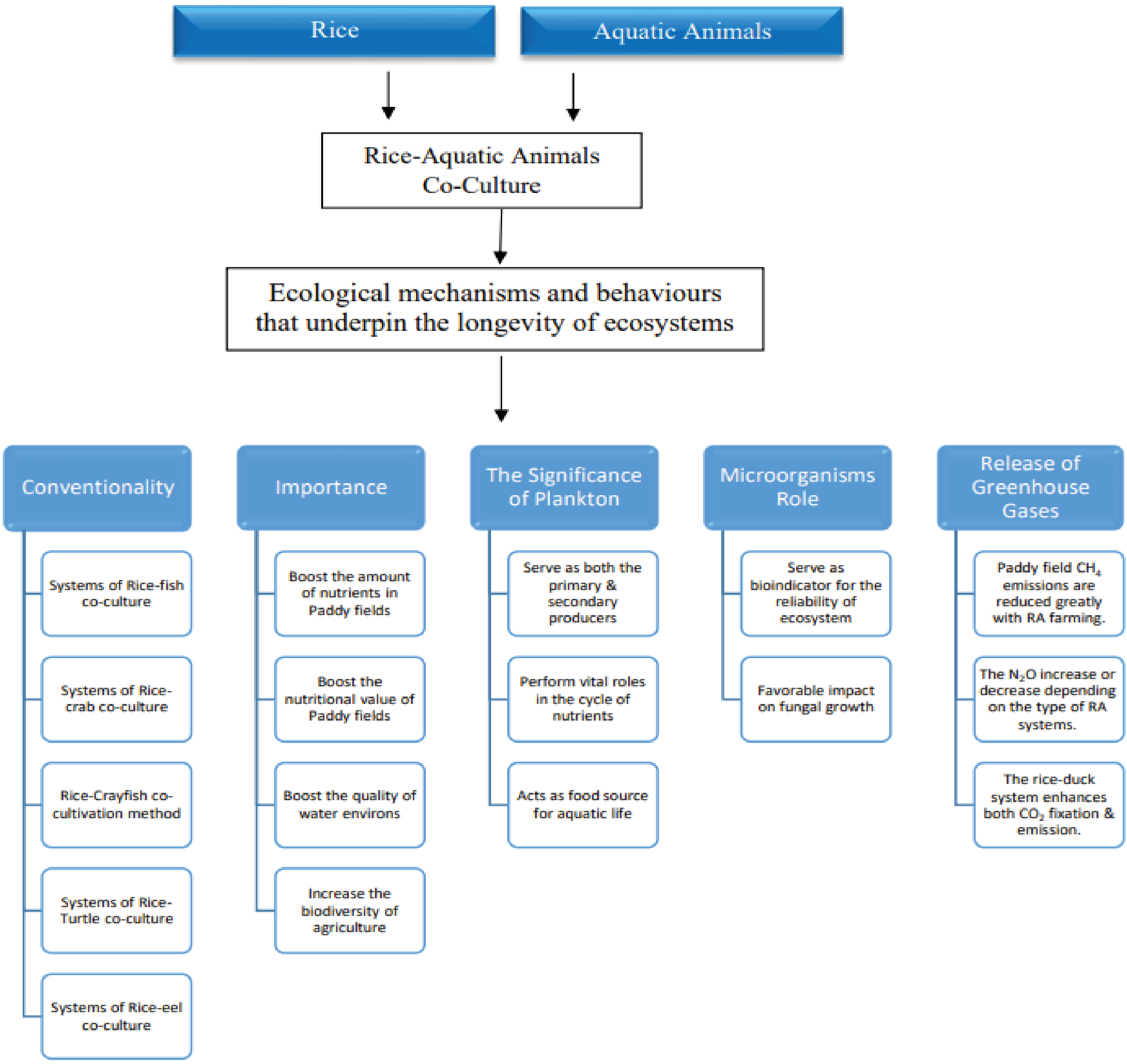
only improve productivity but also enhance the adaptability ratio for climate change and upstream dam impacts [41].

CRA involves beneficial interactions between organisms to improve water use efficiency. Rice provides shade and lowers water temperatures, benefiting aquatic animals. Animal movement benefits soil quality and nutrient availability, while also controlling pests and reducing the need for pesticides [42,43]. However, year-round flooding can lead to reduced soil fertility and other negative changes in soil properties. CRA is an efficient and sustainable way to utilize nutrients. Excess N in rice is absorbed by aquatic animals such as fish, crabs, and shrimps, preventing runoff during the rainy season. The animal waste then becomes nutrients for the rice, thus accelerating the nutrient cycle. In addition, fish that consume the remaining N from rice fields can be sold in the market, thereby improving the socioeconomic status of rural communities. In Bangladesh, CRA is now basic part of green economy and integrated management of land, water and aquatic resources [12,42].



CH_4: methane; N_2O: nitrous oxide; RA: rice-aquatic animals; CO_2: carbon dioxide

Figure 2. Impact of CRA on ecological mechanisms and behaviors that underpin the longevity of the ecosystem.

Socioeconomics Benefits

CRA is an important strategy for farmers to optimize resource utilization and improve socioeconomic status. Since 1970, this system has attracted global attention, especially in China, where the government has taken measures to support farmers in transitioning to precision farming. This shift to cultivated rice is intended to increase productivity, increase farm income and increase resilience to climate change and the impact of upstream dams. Integrated rice farming has significant advantages. In CRA system the fish production has also increased significantly, reaching 600 kg ha^{-1} ya^{-1} [12]. The market price of rice is as high as US\$1.52 kg^{-1}, while the market price of traditional monoculture rice is US\$0.61-0.91 kg^{-1}

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[44,45]. This price premium is attributed to the ecological benefit of fish consuming weeds and insects, which reduces the need for pesticides and herbicides, thereby improving food security [33].

Using the crayfish in CRA, the cost of synthetic fertilizers and chemical pesticides was reduced by 79.5% and 50.0% respectively compared with rice monoculture, while the net ecosystem economic budget (NB) increased by 26.90-75.60%. In addition, the rice-crab co-culture system significantly improved NB, and the positive aspects of bigeye crabs and juvenile crabs far exceeded that of rice monoculture. Overall, the net income of co-culture systems can be 115% higher than that of fish monoculture, demonstrating significant economic and ecological benefits [12,46].

Limitations and Challenges

The adoption of CRA is hindered by factors such as technical proficiency, risks associated with floods and droughts, and the need for integrated management. Lack of technical knowledge, financial support and poor management are significant limitations. Excessive use of chemical fertilizers and pesticides affects habitats and aquatic animal production. Expanding co-culture areas without considering market demand may result in reduced product value and price. Challenges include environmental contamination, excessive competition between organisms, and economic losses due to installation costs and predator attacks. The study also points to the need for better training of farmers and incentives to adopt CRA instead of rice monoculture.

Conclusions

Rice cultivation relies majorly on chemical fertilizers, especially nitrogen fertilizers, to ensure food security. Farming aquatic animals alongside rice can bring economic, ecological and social advantages. But challenges such as lack of technical knowledge and poor management hinder widespread adoption. The review concludes that CRA offer several advantages over monoculture systems and can increase agricultural yields, incomes and land/water use. However, its effects on water quality and greenhouse gas emissions are uncertain and may vary depending on climate and site conditions. Co-culture can reduce greenhouse gas emissions and improve water quality, but may also lead to increased greenhouse gas emissions. Addressing vulnerabilities to climate change, such as droughts and floods needs a strong policy roadmap.

Modulating the intensity and extent of co-culture is critical to maintaining product quality and price while controlling eutrophication and feed application at scale. Optimization of CRA requires further workshops, technical training and problem-solving efforts. Persistent management and business plans, public-private partnerships and technical support are critical. Further research is required to understand the impact of CRA on GHGs, water quality, and biodiversity. Scientific investigations should focus on feed quantity and quality, climatic effects, system optimization and the suitability of co-culture under various conditions. The environmental and ecological effects of CRA require further research to understand its impact. Key issues include studying its impact on the ecology, soil and water environment, improving feeding methods, and identifying suitable rice varieties to provide farmers with technical knowledge and the use of spatially accurate measurement techniques to study greenhouse gas emissions and climate change are critical. Other developing countries are advised to learn from China's approach to overcoming initial investment challenges in rural communities through educational activities and supportive policies.

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No potential conflict of interest was reported by the authors.

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