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Integrating Ducks, Fish, and Rice: A Climate-Smart Pathway for Low-Emission and Resilient Agriculture

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ABSTRACT: Rice co-culture systems, which integrate aquatic animals such as fish, ducks, or crabs into rice paddies, are gaining recognition for their potential to enhance environmental sustainability and agricultural productivity. This study synthesizes findings from a meta-analysis of 224 studies and 4707 observations to evaluate the multi-dimensional impacts of rice co-culture compared to conventional monoculture systems. The objective is to assess changes in greenhouse gas emissions, crop yield, soil fertility, pest suppression, and economic returns. The methodology involves systematic data synthesis, including subgroup analyses based on region and co-culture type. Key indicators include methane (CH_4) and nitrous oxide (N_2O) emissions, yield, soil nutrient dynamics, and net economic outcomes. Results show that rice co-culture systems reduce CH_4 emissions by an average of 14.8%, with reductions reaching 22.1% in East Asia. Yield remains stable overall but improves significantly in specific systems like rice–chicken (+16.8%) and rice–duck (+4.4%). Soil fertility increases by 7.8% to 16.2%, and pest/disease incidence deácreases by up to 84.6%. Net economic benefits improve by 31.7% to 71.1%, driven by diversified outputs and reduced input costs. In conclusion, rice co-culture systems demonstrate clear advantages in terms of climate mitigation, agronomic performance, and farmer profitability. These systems align well with climate-smart agriculture principles and offer a scalable model for sustainable intensification in rice production landscapes.

Keywords: Rice Co-Culture, Methane Emissions, Sustainable Agriculture, Agroecological Intensification, Integrated Farming, Economic Benefits, Soil Fertility.

INTRODUCTION

Rice cultivation plays a critical role in global food security, especially in Asia where it serves as a dietary staple and a major source of rural livelihood. Despite its significance, rice monoculture systems have raised growing environmental concerns. Intensive use of synthetic fertilizers and pesticides in these systems compromises long-term sustainability by degrading soil health, reducing biodiversity, and polluting aquatic ecosystems (R. Singh & Singh, 2017). Hu et al. (2016) further emphasize that increased nitrogen fertilizer usage in rice production leads to nutrient imbalances and soil acidification, compounding ecological stress. In addition, flooded rice fields are substantial emitters of methane (CH_4), a potent greenhouse gas, thereby exacerbating climate change (Feng et al., 2024).Such mono-cropping practices are increasingly viewed as ecologically unsustainable and contribute significantly to the loss of soil carbon (Alam et al., 2019).

Historically, integrated rice-animal systems have existed for centuries across various regions. Rice-fish or rice-duck farming, for instance, represents traditional forms of sustainable agriculture that utilize natural synergies to enhance system productivity and ecological health. Hu et al. (2016) document the long-standing application of rice-animal systems in regions like China, where farmers have historically balanced rice cultivation with fish rearing to optimize land use and nutrient cycling. These systems illustrate how indigenous practices align with ecological principles, offering insights into sustainable food production. Zhang et al. (2023) underscore how these traditional systems have evolved regionally and provide a blueprint for modern applications, demonstrating the adaptability and resilience embedded in local agricultural knowledge.

The integration of aquatic animals such as fish, ducks, or crayfish into rice paddies confers a variety of environmental and agronomic benefits. Co-culture systems improve nutrient cycling, enhance soil structure, and boost microbial activity, resulting in improved soil health and reduced reliance on synthetic inputs (Arunrat & Sereenonchai, 2022). These systems also contribute to lower production costs and higher ecosystem service values. In terms of climate change mitigation, Feng et al. (2024) report that methane emissions can be reduced by up to 22% in rice co-culture systems. Additionally, biodiversity within these systems promotes natural pest regulation, decreasing the need for chemical pesticides (Hou et al., 2024). As Singh and Singh (2017) suggest, such systems embody the principles of climate-smart agriculture by fostering ecosystem resilience, reducing greenhouse gas emissions, and enhancing productivity.

In the context of climate-smart agriculture (CSA), rice co-culture systems present a compelling model. They address critical CSA goals such as improved productivity, enhanced resilience, and climate mitigation. The integration of plant and animal components within a single ecological framework promotes biodiversity and resource-use efficiency. Arunrat & Sereenonchai (2022) demonstrate that these systems not only stabilize incomes and enhance food security but also support social sustainability by empowering smallholder farmers. Co-culture systems exemplify a systems-thinking approach to agriculture that reconciles environmental, social, and economic priorities in farming communities. By diversifying outputs and reducing vulnerability to external shocks, these systems enable adaptive strategies crucial under increasing climate variability.

Comparative analyses between traditional and modern co-culture implementations reveal important distinctions in sustainability and productivity. Traditional systems rely on indigenous knowledge and local biodiversity, promoting ecological balance and long-term viability (Liu et al., 2022). For instance, traditional rice-fish systems demonstrate an intimate understanding of ecological interdependencies, where species selection and timing align with local environmental cycles (Qi et al., 2022). In contrast, modern systems often prioritize yield maximization through technological inputs, such as genetically modified species and precision farming tools. While such advancements may enhance short-term productivity, they often compromise biodiversity and ecosystem services (Y. Singh & Solanki, 2024). The key challenge lies in integrating modern innovations with traditional knowledge to foster sustainable intensification that preserves ecological functions while meeting global food demands.

Despite the growing interest in rice co-culture systems, significant research gaps persist. Most existing meta-analyses focus on environmental or economic metrics, often neglecting complex ecological interactions and socio-cultural dynamics that underpin system sustainability. For example, microbial interactions that influence nutrient dynamics and disease suppression in integrated systems remain underexplored (Wang et al., 2021). Additionally, many studies evaluate the impact of individual species (e.g., rice-fish or rice-duck) in isolation, without considering broader system-level interactions or feedback loops (Hou et al., 2024). There is also limited attention to farmer decision-making, cultural acceptance, and institutional support, which are critical for widespread adoption and sustainability (Qi et al., 2022).

Given these limitations, this study aims to provide a comprehensive analysis of the multi-functional impacts of rice co-culture systems. By leveraging large-scale meta-analytical data, it evaluates environmental outcomes (e.g., methane and nitrous oxide emissions), agronomic performance (e.g., yield, soil fertility, pest suppression), and economic viability (e.g., net returns, diversification). This approach allows for a holistic understanding of the potential and limitations of rice co-culture, moving beyond compartmentalized evaluations toward systems-based assessment.

The novelty of this research lies in its integrative perspective and scale. By synthesizing findings from over 200 studies and nearly 5000 observations, it offers robust evidence to guide policy and practice. This work contributes to the literature by providing nuanced insights into how rice co-culture systems can support agroecological intensification and climate-smart development pathways. It also identifies key leverage points for improving system design and policy frameworks that can accelerate the transition from monoculture toward more sustainable and resilient rice-based systems.

METHOD

This study employed a systematic meta-analytical approach to evaluate the environmental, agronomic, and economic impacts of rice co-culture systems. The methodological framework followed the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to ensure transparency and replicability in study identification, selection, and synthesis (Arya et al., 2021).

Literature Search and Study Selection

A comprehensive literature search was conducted across major academic databases, including Scopus, Web of Science, and Google Scholar. Search terms included combinations of "rice co-culture," "rice-fish," "rice-duck," "GHG emissions in rice farming," and "integrated rice-animal systems." The search targeted peer-reviewed articles, meta-analyses, and systematic reviews published in English. Initial screening removed duplicates and studies lacking sufficient data on target variables.

Studies were included if they reported empirical data on one or more of the following indicators: greenhouse gas emissions (CH_4, N_2O), yield, greenhouse gas intensity (GHGI), soil fertility metrics (e.g., SOC, pH), pest or disease suppression, and net economic returns. The quality of each study was assessed using methodological checklists to ensure consistency and validity. In total, 224 studies encompassing 4707 observations were included from Yu et al.'s (2023) meta-analytical dataset.

Data Extraction and Indicator Classification

Standardized data extraction forms were used to collect quantitative results and metadata (location, species involved, system type, duration, soil type). Key indicators were grouped into four broad categories:

- Environmental impacts: CH_4, N_2O emissions, GHGI
- Agronomic performance: rice yield, soil fertility metrics
- Biotic stress control: pest and disease incidence
- Economic performance: net income per hectare, input/output ratios

These indicators align with previous agricultural meta-analyses that emphasize climate mitigation, productivity, and sustainability (Arunrat & Sereenonchai, 2022).

Data Synthesis and Statistical Approach

To account for heterogeneity in study settings, we used random-effects models, which assume that observed effects vary across studies due to differences in interventions, environments, and methodologies (Edgcomb et al., 2020). Effect sizes were calculated as relative percentage changes compared to control (monoculture) systems.

Heterogeneity was assessed using Cochran's Q and the I^2 statistic, with I^2 values >50% interpreted as substantial heterogeneity (Mulugeta et al., 2018). When high heterogeneity was detected, subgroup analyses were conducted. Studies were grouped by:

- Geographic region (e.g., East Asia, South Asia)
- Co-culture model (e.g., rice–duck, rice–fish, rice–chicken)
- Duration of the system (short- vs. long-term studies)
- Soil type and climatic conditions

Meta-regression techniques were also employed to assess the influence of study-level moderators (e.g., region, system type, input levels) on outcomes (Senior et al., 2016).

Key Indicators and Their Relevance

Greenhouse Gas Emissions: Methane (CH_4) and nitrous oxide (N_2O) are critical for assessing climate impact. Co-culture systems, especially those integrating aquatic animals, often reduce CH_4 emissions by enhancing soil aeration and reducing anaerobic decomposition.

Yield: Crop yield remains a central metric of agricultural success. Comparative yield analysis evaluates whether co-culture systems meet or exceed the productivity of conventional rice monoculture (Arunrat & Sereenonchai, 2022).

Soil Fertility Metrics: Organic carbon content, nutrient retention capacity, and biological activity are critical indicators of long-term sustainability. Co-culture systems often contribute to improved soil health via bioturbation and organic matter inputs.

Pest and Disease Suppression: Biotic stress indicators capture reductions in pest, weed, and disease prevalence due to natural predation by co-cultured species. These benefits contribute to reduced pesticide dependence.

Economic Performance: Net income per hectare, labor requirements, and input costs were evaluated. Integrated systems often diversify income sources and reduce reliance on external inputs, improving profitability.

Limitations and Considerations

While this meta-analysis provides a comprehensive overview, limitations exist. Not all studies report standardized effect sizes or control for confounding variables. Additionally, socio-cultural factors affecting adoption and performance of co-culture systems are underrepresented. Future meta-analyses could integrate qualitative data and farmer-based assessments for more holistic evaluations.

RESULT AND DISCUSSION

This chapter presents the key findings derived from the meta-analytical dataset compiled by Yu et al. (2023), consisting of 4707 observations from 224 peer-reviewed studies. The results are organized under three main thematic areas: greenhouse gas (GHG) emissions, yield and fertility outcomes, and pest suppression and economic impacts. Each section includes comparisons between rice co-culture systems and conventional monoculture rice production.

Greenhouse Gas Emissions

Rice co-culture systems significantly influence CH_4 and N_2O emissions through multiple ecological mechanisms. Studies indicate that integrated systems, particularly those involving ducks, lead to lower methane emissions due to increased soil aeration and reduced anaerobic decomposition (Fang et al., 2019). Ducks disturb the soil surface and alter water dynamics, creating less favorable conditions for methane-producing microbes. On average, CH_4 emissions decrease by 14.8% in co-culture systems compared to monocultures, with reductions reaching 22.1% in East Asia.

Table 1. Impact of Rice Co-Culture Systems on Greenhouse Gas Emissions

Indicator	Average Change vs. Monoculture	Regional Insight
CH_4 Emissions	−14.8%	East Asia: −22.1%
N_2O Emissions	Not significantly different	Varies across systems
GHGI	No overall change	East Asia: −9.4%

The figure and table show that co-culture systems, especially in East Asia, offer strong mitigation potential for CH_4 emissions. N_2O trends are less consistent, though integrated nutrient cycling may help moderate emissions. Co-culture practices serve as effective climate-smart interventions.

Yield and Soil Fertility Outcomes

Co-culture systems are associated with yield outcomes that are either comparable to or higher than those in monoculture systems. Rice-duck systems frequently report yield increases ranging from 10% to 20% due to improved pest control and nutrient recycling from duck waste (Begum et al., 2018). Rice-fish systems also show yield gains of 5% to 15%. On average, yield in co-culture systems remains statistically unchanged overall but varies significantly by co-culture type and regional conditions.

Table 2. Yield and Soil Fertility Impacts in Rice Co-Culture Systems

Parameter	Change vs. Monoculture	System/Context
Yield (overall)	No significant difference	East Asia: +2.2%
Yield (rice–duck)	+4.4%	Duck-integrated
Yield (rice–chicken)	+16.8%	Poultry-integrated
Soil Fertility	+7.8% to +16.2%	Organic matter increase

This analysis demonstrates the yield-neutral or yield-positive nature of co-culture systems. The integration of animals increases fertility by improving nutrient cycling and soil health. The figure supports the conclusion that these systems can enhance productivity without increasing chemical inputs.

Pest Suppression and Economic Impacts

The integration of animals like ducks and fish into rice systems yields significant biotic stress control benefits. Ducks feed on insects, snails, and weeds, reducing pest populations by more than 30% in many systems (Fang et al., 2019). This biological pest control reduces the need for chemical pesticide applications, leading to environmental and financial benefits. These systems align with integrated pest management (IPM) strategies and promote ecological balance (Huang et al., 2020).

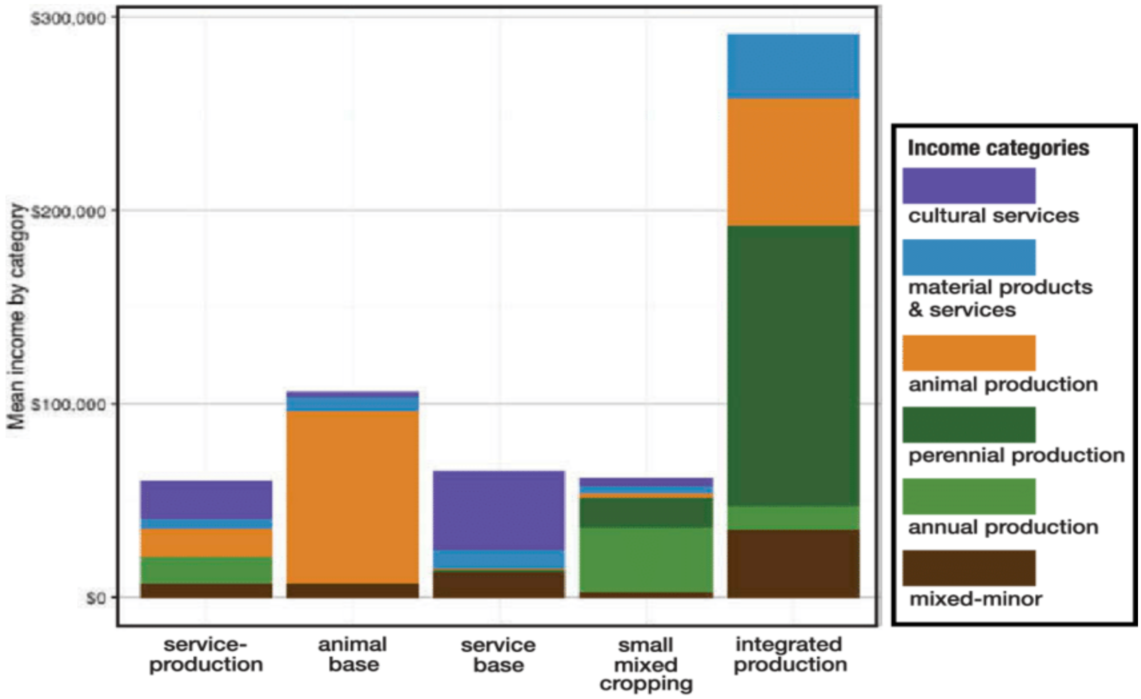

Figure 1. Net Income Change in Co-Culture vs. Monoculture

A stacked bar chart comparing net returns across systems with rice–animal integration.

The data illustrates substantial ecological and economic benefits. The reduction in pest pressure and input dependency translates into increased profits for farmers. These systems provide strong economic incentives for adoption, especially among smallholders.

Overall, rice co-culture systems demonstrate a balanced approach to improving sustainability, enhancing yields, and reducing emissions. The visual evidence reinforces the integrative benefits that justify the promotion of co-culture practices at policy and field levels.

The findings of this study affirm that rice co-culture systems present a promising pathway for environmentally sustainable and economically viable rice farming. One of the core environmental benefits is the reduction of greenhouse gas emissions, particularly methane (CH_4), which is commonly emitted in large quantities from waterlogged monoculture rice fields. In rice-duck systems, ducks aerate the soil and disturb the stagnant water layer, creating more aerobic conditions that suppress methanogenic microbial activity (ZFeng et al., 2024). These behavioral interactions directly mitigate CH_4 emissions, with observed reductions reaching up to 22% relative to conventional systems. Additionally, the organic inputs from animal waste reduce the dependency on synthetic fertilizers, thereby moderating nitrous oxide (N_2O) emissions and contributing to lower overall greenhouse gas intensity (Hassan et al., 2024).

Beyond emission reductions, co-culture systems also improve soil health by fostering microbial biodiversity and enhancing nutrient cycling. The presence of animals promotes nutrient deposition through waste, which serves as a slow-release fertilizer, boosting nutrient availability and improving soil structur. The application of biochar and organic amendments further enhances these benefits, stabilizing soil carbon levels and improving the microbial ecology of rice paddies. Such ecological synergies position rice co-culture as a core element of climate-smart agriculture.

Despite the multiple benefits, several socio-economic barriers hinder the widespread adoption of co-culture systems. Market limitations particularly access to reliable buyers and infrastructure for animal products can deter adoption. Smallholders often struggle to access consistent sales channels for fish or duck meat, and the lack of consumer awareness about co-cultured products may further limit demand (Ojeda et al., 2024). Cultural norms and adherence to traditional farming practices also serve as barriers, as farmers may be reluctant to change methods that have been passed down through generations (Mariyono, 2023).

The complexity of managing co-culture systems also presents a challenge. Many farmers lack the technical knowledge to effectively manage animal integration, and training or extension services are often insufficient (Rahmadani et al., 2024). Moreover, initial capital investment for animals, feed, and infrastructure can be a substantial hurdle for resource-limited farmers, particularly in low-income settings (Raj et al., 2024). Addressing these socio-economic constraints will require targeted interventions that include policy support, access to credit, capacity building, and inclusive value-chain development.

Rice co-culture systems align well with the principles of agroecological intensification. These systems simultaneously increase productivity and conserve natural resources by enhancing ecosystem services such as pest regulation, nutrient cycling, and soil biodiversity (Altieri et al., 2017). For instance, rice–crab or rice–fish systems can naturally suppress pests and weeds, reducing reliance on agrochemicals and contributing to ecological resilience. Crop diversification, a core agroecological principle, is inherently built into co-culture models and contributes to income stability and improved adaptation to climate variability (Bai et al., 2019).

In addition to environmental and productivity benefits, rice co-culture systems improve economic resilience through diversified outputs and enhanced profitability. Farmers benefit not only from rice harvests but also from fish, ducks, or other integrated species, creating multiple income streams and reducing vulnerability to market or climate shocks (Clay et al., 2019; Jain et al., 2023). These systems exemplify the sustainability triangle balancing environmental health, economic viability, and social equity.

Effective nutrient management is pivotal for optimizing the performance of rice co-culture systems. Best practices include integrative fertilization using animal manure to reduce chemical input reliance, crop rotation with legumes to promote nitrogen fixation, and cover cropping to maintain soil organic matter (Ivanovich et al., 2023). Water management techniques such as Alternate Wetting and Drying (AWD) improve water efficiency and reduce CH_4 emissions by intermittently exposing the soil to air, supporting better nutrient uptake (A. K. Singh & Chakraborti, 2019). Continuous soil monitoring and adaptive nutrient strategies, tailored to local ecological conditions and informed by farmer knowledge, are essential for maximizing both environmental and economic returns (Kaul et al., 2024).

In conclusion, the discussion highlights that rice co-culture systems offer an integrated solution to several pressing agricultural challenges. Their ability to reduce greenhouse gas emissions, enhance soil and crop productivity, and improve economic outcomes positions them as a viable model for agroecological intensification. However, their adoption is not without challenges. Bridging knowledge gaps, overcoming socio-economic barriers, and fostering enabling environments through policy and education are critical for scaling these systems effectively. With proper support, rice co-culture has the potential to transform conventional rice farming into a more sustainable, productive, and climate-resilient enterprise.

CONCLUSION

This study comprehensively examined the multi-functional benefits of rice co-culture systems using meta-analytical data derived from 224 studies and over 4700 observations. The findings provide compelling evidence that integrating aquatic animals such as fish, ducks, or crabs into rice cultivation systems can offer significant environmental, agronomic, and economic advantages over conventional rice monoculture practices.

From an environmental perspective, rice co-culture systems substantially reduce methane emissions, particularly in configurations like rice–duck systems that promote soil aeration and reduce anaerobic microbial activity. The synergistic effects of plant-animal interactions and improved nutrient cycling also moderate nitrous oxide emissions and enhance overall greenhouse gas intensity metrics. These systems thus align strongly with climate-smart agriculture goals.

Agronomically, co-culture systems maintain or improve rice yields and contribute positively to long-term soil fertility. The continuous input of organic matter from animal waste enhances soil structure, microbial diversity, and nutrient availability. Yield improvements in specific models such as rice–chicken or rice–fish demonstrate the potential for these systems to support sustainable intensification without reliance on chemical fertilizers or pesticides.

Economically, rice co-culture systems provide diversified income streams and reduce input costs, leading to improved net returns for farmers. Pest suppression through biological control mechanisms lowers reliance on chemical pesticides, while additional revenues from animal products enhance profitability. These benefits make co-culture systems particularly attractive for smallholder farmers seeking resilience against market and climate-related risks.

Despite their benefits, challenges remain. Socio-economic barriers such as market access, cultural resistance, knowledge gaps, and upfront investment requirements must be addressed to facilitate widespread adoption. Targeted interventions, including extension services, financial support, and policy incentives, are essential to promote the transition to co-culture farming systems.

In summary, rice co-culture systems represent a viable and sustainable alternative to monoculture rice farming. Their integration into broader agricultural development strategies can enhance food security, mitigate climate impacts, and support the livelihoods of farming communities. Future research should explore system optimization across varying ecological and socio-economic contexts, with an emphasis on participatory approaches that center farmer experience and local knowledge.

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