

October 2025

Agroecology and Integrated Rice– Fish Systems: Pathways to Food and Nutritional Security in Eastern India

Ayan Samaddar, Sonali Singh, Nilendu Basak, Sudharsan Malaiappan, Rajib Majumder, Neetha Shenoy, Shwu Jiau Teoh, Arun Padiyar, Sarah Freed, Subrata Saha



Authors:

Ayan Samaddar*¹, Sonali Singh², Nilendu Basak^{3,4}, Sudharsan Malaiappan⁵, Rajib Majumder⁶, Neetha Shenoy¹, Shwu Jiau Teoh⁷, Arun Padiyar¹, Sarah Freed⁸, Subrata Saha⁹

¹ WorldFish-Odisha Program Office, Plot No. A15, Sharma Street, Unit 7, Surya Nagar, Bhubaneswar 751025, Odisha State, India

² IFPRI South Asia Office. NASC Complex, CG Block Dev Prakash Shastri Road (Opp. Todapur). Pusa, New Delhi 110012 India,

³Department of Microbiology, University of Kalyani, Kalyani 741235, West Bengal, India

⁴Department of Civil and Environmental Engineering, Indian Institute of Technology Delhi, Hauz Khas, New Delhi - 110016, India

⁵ International Water Management Institute (IWMI), New Delhi, India,

⁶Department of Zoology, Vivekananda Mahavidyalaya · Haripal, Hooghly- 712405, West Bengal, India,

⁷ WorldFish Malaysia, Jalan Batu Maung, Batu Maung, 11960 Bayan Lepas, Penang, Malaysia.

⁸ International Center for Tropical Agriculture (CIAT), Kenya.

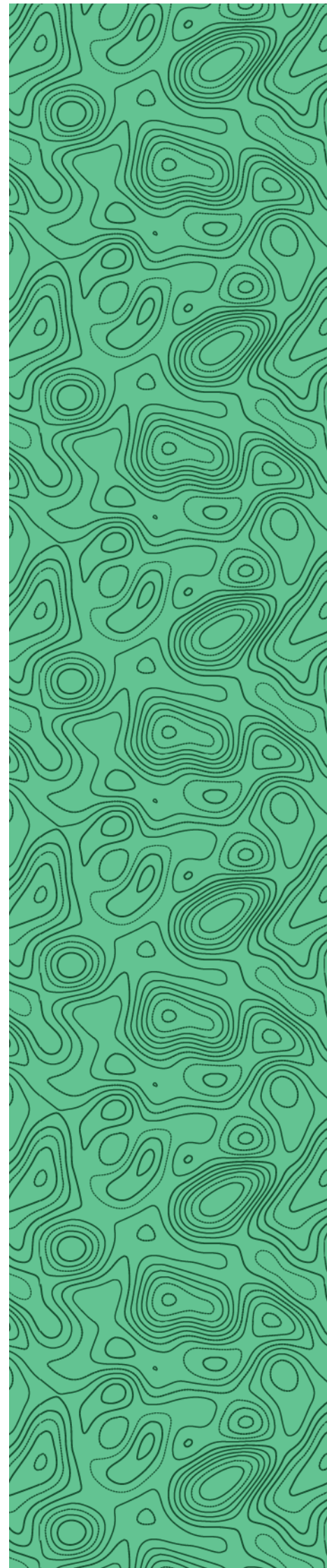
⁹ Centre of Decision Science and Optimisation, University of Engineering and Management, Kolkata, West Bengal, India

Acknowledgments:

This work was funded by the CGIAR Initiative on Agroecology and by the CGIAR Multifunctional Landscapes Science Program. The authors wish to acknowledge Glenn Hyman (Consultant Editor to the Alliance of Bioversity International and CIAT Science Writing Service) for copy editing of this manuscript.

Contents

Acronyms	3
List of Tables	4
List of Figures	4
Abstract	5
1. Introduction	6
2. Methods	9
2.1. Search methodology and inclusion criteria	9
2.2. Data processing and analysis	11
3. Results	12
3.1. Aligning IRFS attributes with agroecological principles	12
3.2. Alignment of agroecological IRFS with addressing FNS	17
3.3. IRFS in Eastern India	18
4. Discussion	24
4.1. How IRFS qualities address agroecological transition	24
4.2. Agroecological IRFS addressing FNS	24
4.3. Eastern India perspective	24
4.4. Research Gaps and Priorities	25
5. Conclusion	27
References	28



Acronyms

AE	Agroecology
APCNF	Andhra Pradesh Community Managed Natural Farming
CGIAR	Consultative Group on International Agricultural Research
DST	Department of Science and Technology
FAO	Food and Agriculture Organization of the United Nations
FNS	Food and Nutritional Security
FNSL	Food, Nutritional Security and Livelihood
HLPE / HPLE	High-Level Panel of Experts on Food Security and Nutrition
ICAR	Indian Council of Agricultural Research
IPCC	Intergovernmental Panel on Climate Change
IRFS	Integrated Rice Fish Systems
NABARD	National Bank for Agriculture and Rural Development
NMNF	National Mission on Natural Farming
NRRI	National Rice Research Institute
PMMSY	Pradhan Mantri Matsya Sampada Yojana
RMS	Rice Monoculture Systems
TAPE	Tool for Agroecology Performance Evaluation
UN	United Nations

List of Tables

- Table 1** Inclusion and exclusion criteria of review protocol
- Table 2** Alignment of AE principles with selective IRFS of Eastern India

List of Figures

- Figure 1** Overview of article sources considered in this study
- Figure 2** Overview of article sources considered in this study (*quantitative publication overview*)
- Figure 3** Aligning IRFS characteristic features with AE principles
- Figure 4** Important ecological factors and mechanisms involved in an integrated rice fish farm environment
- Figure 5** AE principles addressing FNS in an IRFS
- Figure 6** Alignment of agroecological principles with selective IRFS of Eastern India
- Figure 7** Key policy recommendation

Abstract

Integrated Rice Fish Systems (IRFS) offer a viable substitute for rice monoculture. They efficiently use the rice field ecosystem's inherent productivity and available resources to provide the farming community with better economic and nutritional gains. IRFS adoption remains poor in Eastern India, despite favorable geographic conditions, natural resource availability, traditional knowledge, necessity for economic growth, and preference of rural communities for a rice and fish-based diet. To investigate whether agroecology (AE) could accelerate an IRFS-based transition towards food and nutritional security (FNS), this review of 194 scientific articles on IRFS from 2004 to 2024 documented the AE traits of IRFS and their relevance to addressing FNS. The current IRFS of Eastern India were assessed, first through a rapid review process to identify their qualitative traits consistent with AE. Next, we evaluated IRFS' impact on FNS. In total, IRFS has shown 52 traits relevant to AE principles and that address FNS. Among 13 AE principles, seven have been considered primary impact creators of FNS. Impact may be accelerated with strategies such as crop diversification, mixed crop-livestock systems, and farmer-to-farmer networks. Fish play a significant role in IRFS by preserving ecological and socioeconomic equilibrium, supporting livelihoods, income, and community engagement. In Eastern India, an analysis of five distinct IRFS types identified qualitative features that could support a maximum of 10 relevant AE principles, but for which pertinent empirical evidence was lacking. Although IRFS could potentially boost smallholder income, FNS, and overall productivity, Eastern India would need to address seven significant challenges, including initial investment costs, vulnerability to natural disasters, hilly terrain, loss of indigenous fish varieties, environmental impacts of inputs, land-use change, limited technical knowledge and financial constraints among the farming communities. AE frameworks can support scaling up IRFS adoption and diffusion through a holistic approach to performance evaluation and creating appropriate strategies and guidelines.

KEYWORDS

Ecosystem, Rice fish productivity, Agroecological principles, Agroecological transition, Food security.

1. Introduction

The United Nations (UN; Declaration, 1996) defines global food security as all people having “physical and economic access to sufficient, safe and nutritious food that meets their food preferences and dietary needs for an active and healthy life.” Rice has long been regarded as the most crucial crop for ensuring food and nutritional security (FNS) for the people of India (Verma et al., 2021). India is one of the leading producers of rice, with a production capacity of 100 million metric tons per year (Sathoria and Roy, 2022). More production may be required to feed India’s rapidly growing population, which is predicted to reach 1.522 billion by 2036 (Chandramouli, 2011). The growing use of chemical fertilizers and pesticides to increase rice productivity may not provide FNS because it poses serious threats to the environment, the economy, human health, and nutrition (Khumairoh et al., 2021; Stadlinger et al., 2018; Kathiresan et al., 2020; Datta et al., 2016, Kaushal and Prashar, 2021; Liu et al., 2019; Swaminathan and Kesavan, 2012). At the same time, the higher cost and limited access to sustainable inputs in India hinders the transition to sustainable farming practices (Paul et al., 2023).

Integrated Rice Fish Systems (IRFS) have been recognized as a viable way to enhance rice production in an environmentally sustainable manner while concurrently generating fish as a secondary crop (Wang et al., 2024; Lansing and Kremer, 2011). This makes IRFS a highly effective economic model for small and marginal farmers (Niyaki and Allahyari, 2011; Mariyono, 2024; Ahmed and Turchini, 2021; Jiao et al., 2023; Zheng et al. 2025). Recently, IRFS have gained attention as a promising approach to advance the agroecological transition in India and ensure FNS (Bisht et al., 2022). IRFS demonstrate the potential to contribute to the optimal use of natural resources, poverty alleviation, income generation, and environmental sustainability (Yuan et al., 2022; Wang and Gao 2017; Rautaray et al., 2005; Yifan et al., 2023; Sathoria and Roy 2022). The 1500-year-old IRFS heritage has been preserved in some of India’s north-eastern states (Assam, Arunachal Pradesh, Nagaland, Manipur, Meghalaya, Tripura, and Mizoram), eastern states (West Bengal and Odisha), and one south-eastern state (Andhra Pradesh). These IRFS combine traditional and scientific methods tailored to diverse landscapes (Halwart and Gupta 2004; Sathoria and Roy 2022). Farmers in these zones practice aquaculture by raising fish in low-lying paddy fields, significantly contributing to FNS and holistic development (Sinhbabu and Poonam 2022). Despite aquaculture’s benefits, the adoption rate of IRFS in Eastern India remains low due to several challenges and issues that have emerged over the past two decades. Low IRFS adoption may result from high initial investments needed to build infrastructure, the vulnerability of low-lying areas to flooding, and limited technical knowledge. Social unrest and out-migration of rice-fish farmers to urban areas have also been considered as some of the important challenges. Moreover, many IRFS zones are currently facing negative impacts from the increasing commercial demand for rice and fish. These conditions are pressuring farmers to adopt more easily operable and productive chemical input-based agricultural methods over IRFS practices, which poses a threat to sustainability (Brahmanand et al., 2009; Mandal et al., 2021; Asada et al., 2022).

India continues to experience a significantly higher rate of malnutrition compared to other modern countries with similar economic growth. Addressing the public health issue of undernutrition will require future efforts to focus on the quality of a nutritious diet (Mandal et al., 2024). In this context, ensuring access to a sufficient and healthy diet has become an increasingly critical aspect of policy-making (Divakar et al., 2024). Fish offers numerous health and nutritional benefits (Thilsted et al., 2016), while rice

serves as an essential and reliable dietary staple food (Debnath et al., 2018). Together, these two foods could play a pivotal role in combating FNS challenges in India (Samaddar et al., 2025b). When combined, rice and fish are unparalleled in their nutritious value and their favorable effects on FNS, as demonstrated in India and many other South Asian nations (Yi 2019; Samaddar et al., 2025b; Freed et al., 2020a; Sathoria and Roy 2022). Therefore, parallel to the rice-based food system's productivity enhancement, Indian researchers and policymakers are now concentrating on improving the nutritional gain to humans (Ge et al., 2023; Wan et al., 2019).

The potential of fish to alleviate hunger, malnutrition, and poverty is indicated by the rising demand for it as a nutrient-dense superfood in India (Padiyar et al., 2024). In many regions of Eastern India, the combination of both rice and fish thus offers a potential solution for dealing with FNS (Samaddar et al., 2025b; Sathoria and Roy 2022; Saikia 2024). Sustainable agricultural growth for human FNS can be achieved through agroecology (Prost et al., 2023), which integrates ecological processes, environmental considerations, public health, and well-being (D'Annolfo et al., 2017; Wezel et al., 2014). Agroecology has gained prominence as a scientific and policy approach to reforming food systems—applicable at the field, farm, and entire food system levels (Phong et al., 2010; Wezel et al., 2009). To evaluate the AE performance of a food system, the Food and Agriculture Organization (FAO) established 10 standardized elements, based on recommendations from a High-Level Panel of Experts (HLPE). The panel further developed 13 principles, which are a consolidated version of FAO's elements (Wezel et al., 2020; HPLE, 2019). The principles can be used for designing and implementing agroecosystems based on sustainable farming. Their adoption provides beneficial effects on the health of the ecosystem and humans, thereby addressing the FNS of smallholder farm households (Herrero et al., 2017; Kerr et al., 2021).

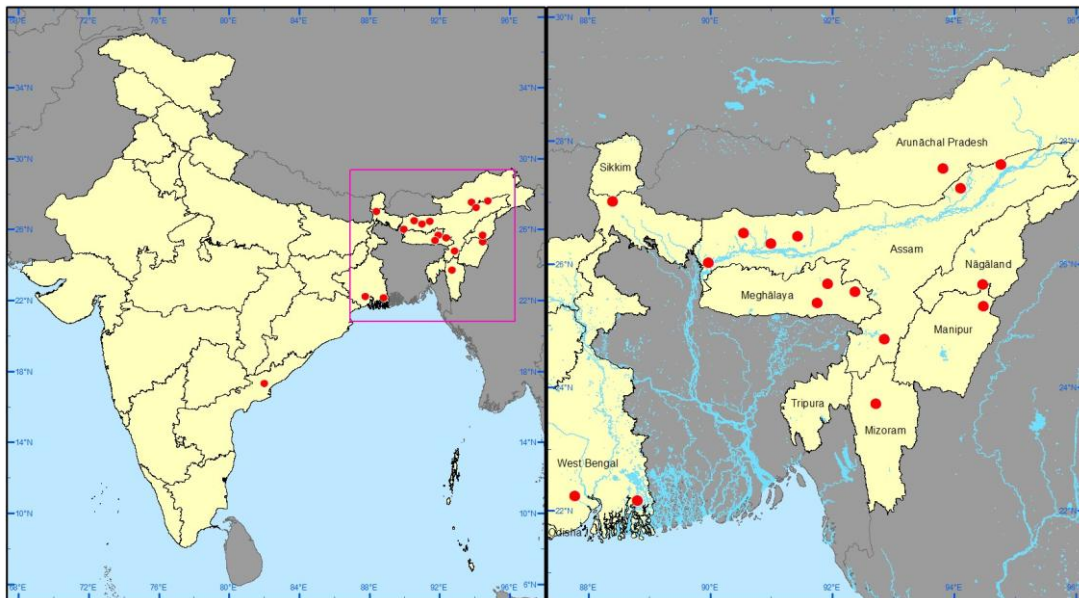
The National Mission on Natural Farming (NMNF) and various regional initiatives drive AE transitions in India. Among these, the Andhra Pradesh Community Managed Natural Farming (APCNF) initiative sets a standard for holistic development by prioritizing FNS (Jaacks et al., 2023). APCNF promotes IRFS alongside other farming methods, demonstrating promising AE impacts (Dorin 2022). These initiatives have garnered interest from international organizations such as the FAO and CGIAR, focusing on environmental and social issues within food systems (Dorin 2022). These efforts align with the agendas of the UN (HPLE, 2019) and the Intergovernmental Panel on Climate Change (Ogunbode et al., 2020). They enhance FNS, promoting knowledge about the AE characteristics of farming systems (Kerr et al., 2021). Subsequent reviews have explored the effects of organic agriculture and diversified farming systems on FNS, yields, and other ecosystem service outcomes (Powell et al. et al., 2015; Reganold and Wachter 2016; Selvan et al. 2023; Sibhatu and Qaim 2018). Agroecological farming could have similar or even more positive effects on FNS (Kerr et al., 2021; Wezel et al., 2020). Therefore, IRFS could serve as a promising model for agroecology (D'Annolfo et al., 2017; Freed et al., 2020a). Its AE assessment has not yet been completed, despite its 37.9% greater efficiency in addressing ecosystem service-related concerns as compared to Rice Monoculture Systems (RMS) (Liu et al., 2020).

This review investigates the evidence for IRFS-based farming to determine if agroecology can enhance FNS. Eastern Indian IRFS could serve as a valuable starting point for addressing this knowledge gap. IRFS-based AE movements could draw on existing traditional IRFS-based food systems developed by Indigenous people in this region—people with local knowledge and resources (Gogoi et al., 2015; Sathoria and Roy 2022; Sinhababu and Poonam 2022). The three main aims of this study are (1) to align the relevant characteristics of IRFS with AE principles, (2) to understand the impact of IRFS on the FNS of rural communities under an AE framework, and (3) to evaluate the AE properties of Eastern Indian IRFS by qualitatively assessing their contribution to local FNS.

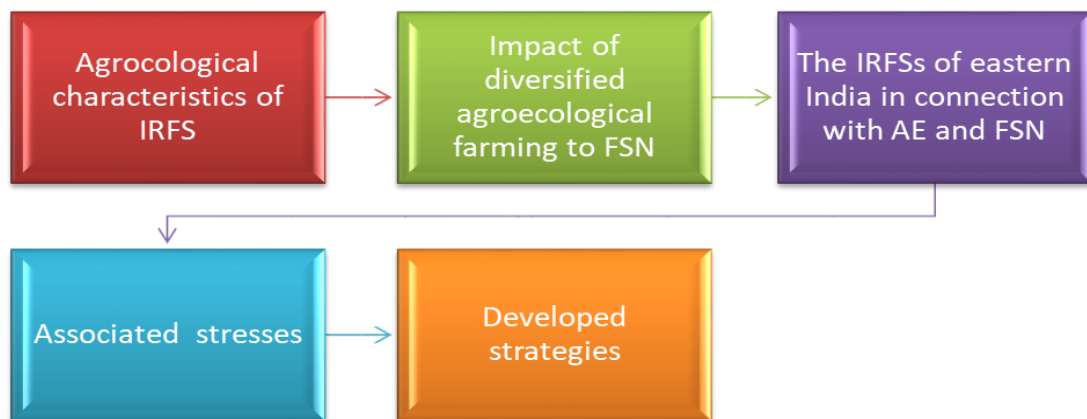
2. Methods

2.1. Search methodology and inclusion criteria

A rapid review methodology supported evidence-based decision-making in the development and management of rice-fish culture systems. Initially, we searched and evaluated published articles to identify the IRFS qualitative characteristics that align with the agroecology (AE) concept. Following this initial article selection and evaluation process, the focus shifted to the second study aim, locating literature within the AE framework that examines or establishes the impact of diverse farming systems, including IRFS, on FNS in rural areas. This search also supported the investigation of potential avenues for qualitatively assessing the capacity of IRFS to deliver FNS through AE. Efforts were then directed towards the third aim, identifying AE IRFS-based evidence from India (Figure 1a).



a. Identified IRFS locations in Eastern India evaluated in the study (point symbols denoted in red).



b. Steps used for the literature survey.

Figure 1. Overview of article sources considered in this study.

Our search sought to recognize key barriers to developmental strategies. During this final search, related stresses and mitigation strategies for IRFS in Eastern India were also considered. The detailed process is illustrated in Figure 1b.

Following the procedures outlined by Kerr et al., (2021), a list of search terms was created by reviewing the abstracts of relevant publications. We evaluated pertinent systematic reviews and databases. The following terms were used while searching the primary database: “paddy farming” OR “rice fish co-culture” OR “rice farming/culture” OR “aquaculture” OR “integrated aquaculture” OR “integrated rice-fish farming” OR “agroecology” OR “agroecological farming” OR “agroecological aquaculture” OR “agroecological rice” OR “The alignment of agroecological principles with rice/fish/rice fish co-culture” OR “rice fish ecosystem” AND “food security” OR “nutritional security” OR “rural areas” OR “impact of IRFS on FNS” OR “food security through rice farming” OR “food security through fish farming and IRFS of Eastern India” OR “ecosystem services” OR “socioeconomic impacts of Eastern Indian IRFS” OR “types or agroecological features of Eastern India IRFS”. Relevant articles were identified through bibliographic databases such as Scopus, Web of Science, and AGRIS, as well as from the official websites of the Government of India, the Food and Agriculture Organization of the United Nations (FAO), CGIAR, and peer-reviewed journals accessible via platforms like SpringerLink, ScienceDirect, and Wiley Online Library. The initial set of inclusion criteria for publications considered publication dates from January 2004 to August 2024. We also used search term definitions to guide the criterion listed in Table 1. Along with inclusion criteria, exclusion criteria for literature were also established. After developing the screening process, abstracts were selected for full-text evaluation. Procedures were implemented to identify and extract pertinent information. We were able to find more publications that we had overlooked by doing impromptu exploratory searches on Scopus and perusing the reference lists of all pertinent articles that our original search yielded.

Criteria for inclusion	Criteria for exclusion
1. Published from January 2004 to August 2024	1. Articles published outside of January 2004 to August 2024 date range
2. Involves IRFS-based evidence	2. Does not include practices that have links to HPLPE's agroecological principles
3. Includes agroecological farming systems	3. Molecular biological techniques and assessments.
4. Reports on human nutrition or food	4. Non-human subjects.
5. Articles of farming system's performance assessment	5. Nonassessable full text or not in the English language
6. Farmer adopted IRFS-based evidence from Eastern India	
7. Academic book, dissertation/thesis, peer-reviewed article, if it is gray literature, then from a reliable source (reputed institutions).	

Table 1: Inclusion and exclusion criteria of review protocol.

2.2. Data processing and analysis

We reviewed a total of 194 peer-reviewed scientific publications. For the first objective, the positive and negative IRFS-based impact-creating traits or parameters were identified in connection to the AE principles (Wezel et al., 2014). The principal or secondary traits or parameters, based on the AE principles (HPLPE, 2019), were classified according to their IRFS-based attributes. For the second objective, Wezel et al.'s (2020) descriptive approach was employed to investigate the direct or indirect effects of the IRFS-inspired AE principles on FNS. For the third objective, AE principles in connection with the FNS were assessed among the Eastern Indian IRFS, as were the challenges and mitigation strategies employed in these IRFS (Figure 2).

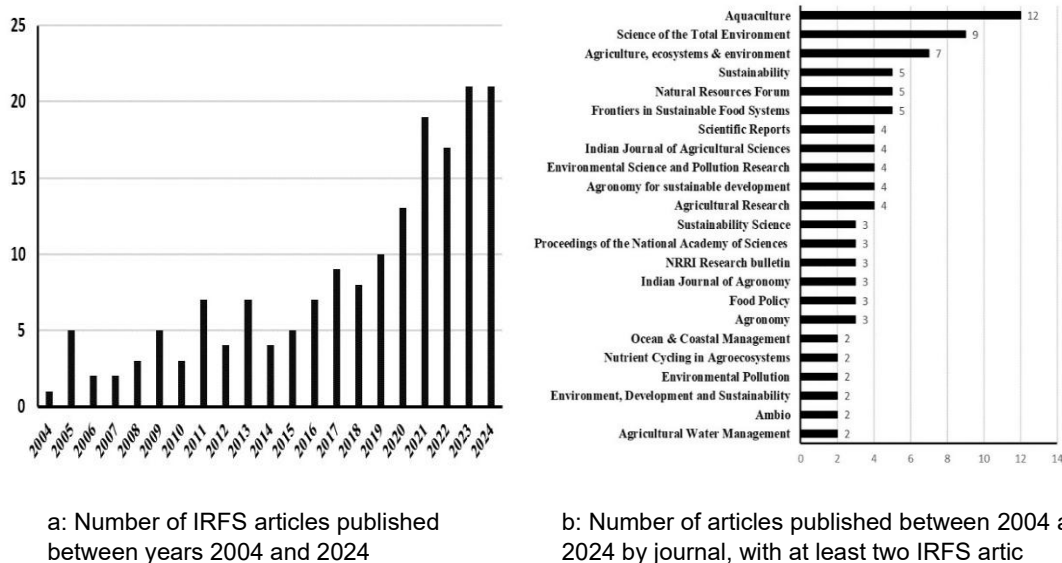


Figure 2. Overview of article sources considered in this study.

3. Results

Figure 2a depicts the number of articles published per year, demonstrating that the growth rate of academic publications related to rice-fish co-culture seems to be exponential since 2014 (Figure 2a). We found that 194 articles were published based on our search criteria.

Researchers published the selected articles on rice-fish co-culture in 102 different journals (Figure 2b). Cumulatively, 22 journals publish close to 53% of articles. The journal *Aquaculture* stands out as the title with the largest number of published articles. The predominance of articles published in aquaculture- and environment-focused journals suggests research orientation toward practical implementation and applied outcomes, rather than purely ecological or theoretical investigations.

3.1. Aligning IRFS attributes with agroecological principles

Relevant IRFS attributes were identified for each of the 13 AE principles (HPLE, 2019). These include ecological and socioeconomic attributes (Figure 3).

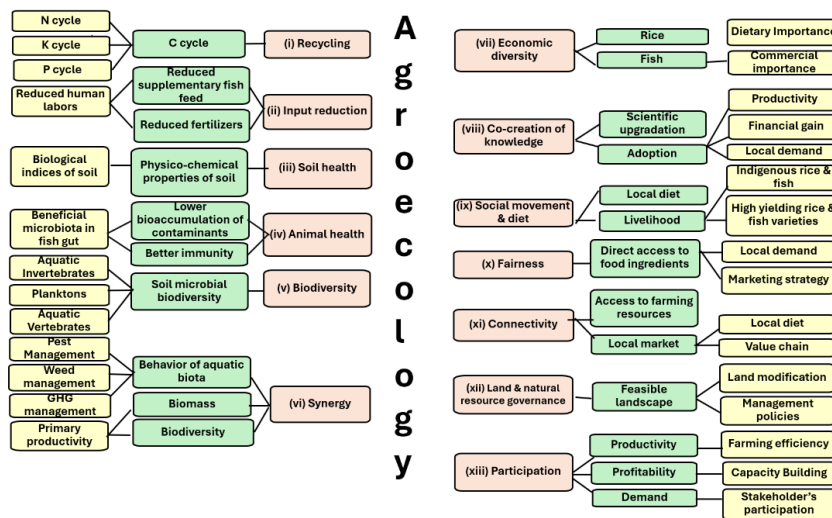


Figure 3. Aligning IRFS characteristic features with AE principles.

Within the IRFS literature, the AE principles of recycling, input reduction, soil health, animal health, and biodiversity were found to primarily relate to the ecosystem. Their interaction supports ecological synergy. In terms of the socioeconomic characteristics of an agrifood system, this literature prioritizes the following agendas: social movements, income generation, and FNS. These topics relate to the AE principles of economic diversity, co-creation of knowledge, social movements and diet, fairness, connectivity, participation, land, and natural resource governance. We identified the attributes that were pertinent to AE principles and separated them into primary and secondary categories. Secondary attributes were determined to be primarily responsible for establishing impact over selected AE principles through the primary attributes or by supporting the primary attributes. Primary attributes were picked for their direct ability to create impact on the targeted AE principles. The AE principles and relevant attributes are explained in the next section, with primarily attributes in bold font. Secondary attributes are in combined bold and italics.

3.1.1. Recycling

IRFS recycle nutrients efficiently (Phong et al., 2010; Xu et al., 2022). These include carbon (C) cycling and sequestration and the recycling of nitrogen (N), phosphorous (P), and potassium (K) (Xu et al., 2022; Chen et al., 2024; Oehme et al., 2007). These four nutrient cycles account for the primary flow of nutrients and energy in IRFS environments (Wei et al., 2019) (Figure 4). Higher C sequestration and the growth of aerobic microorganisms in the soil

illustrate higher nutrient recycling in IRFS as compared to RMS (Xu et al., 2022; Bhattacharyya et al., 2022; Stockmann et al., 2013; Wei et al., 2019). Additional improvement in nutrient recycling efficiency appears to be achievable with the judicious application of supplemental nutrient-rich inputs (fish feed, fertilizers, etc.) to enhance the production of both rice and fish with higher profitability (Goda et al., 2024; Halwart and Gupta 2004).

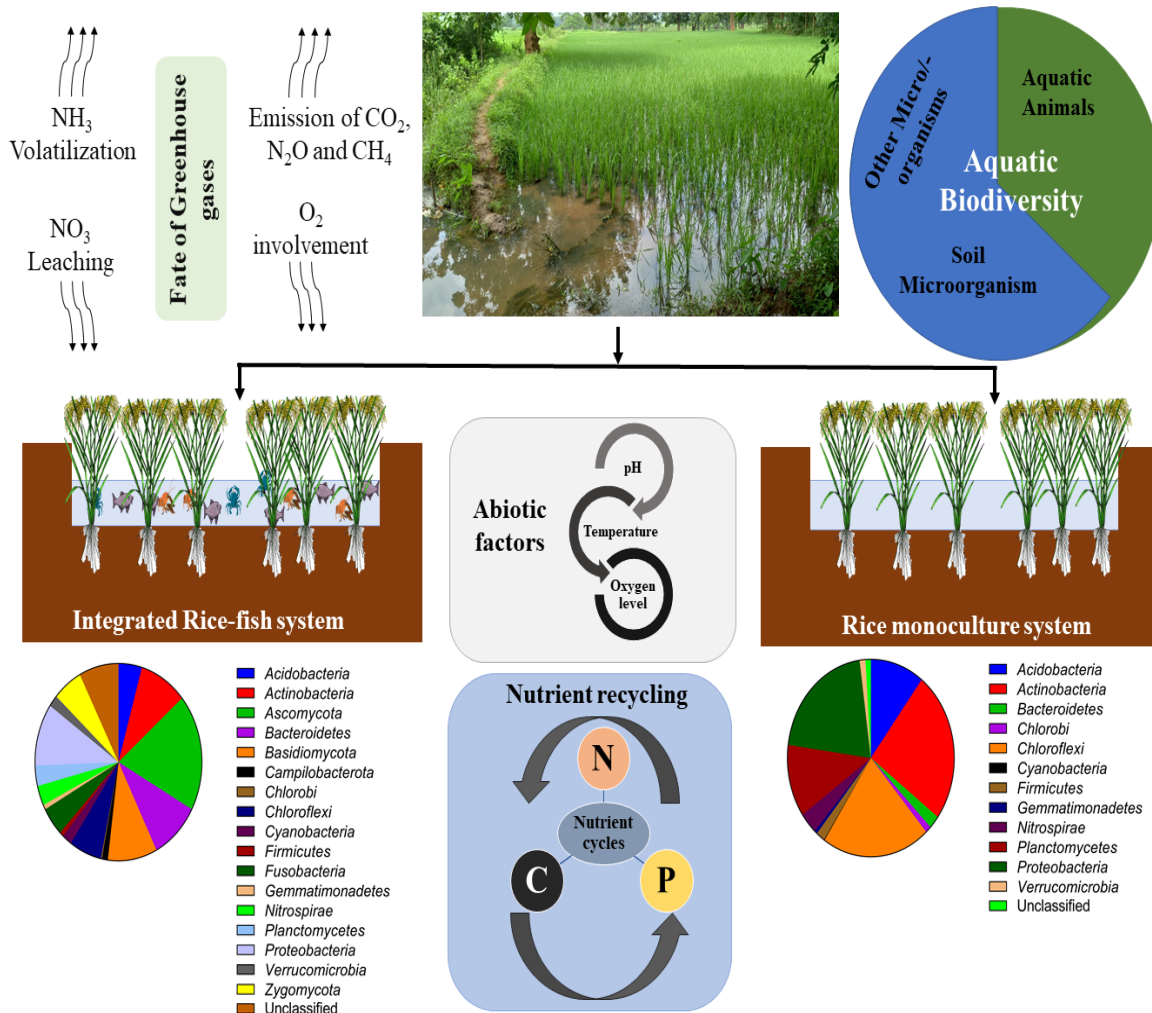


Figure 4: Important ecological factors and mechanisms involved in an integrated rice fish farm environment

3.1.2. Input reduction

In IRFS, efficient nutrient recycling and enhancing soil fertility improves the abundance of total oxidizable organic C, as well as phosphorus, potassium, and nitrogen (Bhattacharyya et al., 2013; Feng et al., 2021; Liu et al., 2024). Nitrogen recycling is mainly responsible for reducing the need for chemical fertilizers as compared to RMS (Xie et al., 2010, 2011; Liu et al., 2024; Yassi et al., 2023). The nutrient recycling and soil fertility properties of IRFS also boost planktonic assemblages and substantially reduce the need for supplementary fish feed as compared to conventional aquaculture farms (Frei and Becker 2005; Billah et al., 2020). IRFS also sustain fish and rice production efficiently by significantly reducing the need for supplemental nutrients (feed and fertilizers), pesticides, herbicides, and human labor (Ahmed et al., 2011). Rice-fish farming generated on average 38% higher net revenue than rice monoculture across all countries combined (Yifan et al., 2023).

3.1.3. Soil health

IRFS can increase soil fertility levels and other ecosystem functions, primarily through C sequestration (Li et al., 2024; Zhang et al., 2023; Nayak et al., 2024). The system demonstrates significant improvements over RMS, in terms of higher C sequestration and oxygenation in soil through optimum use of organic inputs (e.g., fertilizers, compost, manures, etc.) (Nayak et al., 2018; Guo et al., 2020; Mohanty et al., 2009). IRFS practices were also found to be responsible for the growth of beneficial microbes in soil (Li et al., 2024; Nayak et al., 2024; Ren et al., 2023). In addition, aerobic microbes are found to enhance soil health by accelerating urease, cellulase, Phosphorylase, and β -glucosidase activity (Liu et al., 2024; Bihari et al., 2015). However, results may differ according to geography, environment, and the practices applied. Nevertheless, the physicochemical characteristics of the soil are expected to improve alongside biological indices facilitated by the beneficial microorganisms in IRFS (Hou et al., 2024).

3.1.4. Animal health

Fish gut microbiota is crucial for better immunity, disease prevention, and overall health (Tao et al., 2022). In IRFS, autonomous assemblages of beneficial microbes positively influence the health of numerous aquatic organisms with commercial importance. The presence or absence of these microbes could serve as key indicators for fish health and immunity (Tao et al., 2022; Huang et al., 2023). Furthermore, IRFS can improve aquatic animals' general health by reducing their assimilation of harmful metals, antibiotics, and carcinogens (Mo et al., 2022; Ning et al., 2022; Duan et al., 2022). Recent observations have shown that IRFS habitats can boost the adaptation capacity of common carp (Cheng et al., 2023, 2024).

3.1.5. Biodiversity

The biodiversity of soil microorganisms could serve as a primary indicator of IRFS ecosystem health and functioning (Herlambang et al., 2021; Myo et al., 2024; Ren et al., 2023). Microbial biodiversity studies reveal Proteobacteria, Chloroflexi, Actinobacteria, Nitrospirae, Bacteroidetes, Chlorobi, Cyanobacteria, Campilobacterota, Verrucomicrobia, Firmicutes, and Verrucomicrobia to be the dominant microbial phyla of diverse IRFS (Arunrat and Sereenonchai, 2022; Tao et al., 2022; Zhao et al., 2021; Duan et al., 2022; Huang et al., 2023) (Figure 4). Soil microbial functioning can boost nutrient availability in IRFS ecosystems (Zhao et al., 2021). Furthermore, nutrient exchange from soil to water (Uwimana et al., 2022) can aid in improving planktonic assemblages in IRFS (Ahmed et al., 2022; Saikia and DN, 2008). The dominant planktonic groups in IRFS-based settings are Chlorophyceae, Cyanobacteria, Cladocerans, Copepods, and Rotifers (Bashir et al., 2020; Saikia and Das, 2015; Saikia 2024). Adequate planktonic abundance allows indigenous aquatic vertebrates and invertebrates to flourish, including commercially significant Cypriniformes, Siluriformes, Crustaceans, Gastropods, and Amphibians as reported from various locations (Lu and Li 2006; Dey et al., 2013; Freed et al., 2020a).

3.1.6. Synergy

IRFS can foster a synergistic ecosystem, encouraging favorable interactions between soil, water, animals, and crops (Zhang et al., 2023). The presence of fish can increase soil and water fertility and O₂ levels in the water (Guo et al., 2022), thereby encouraging microbial density and metabolic rate in the rhizosphere and soil (Ren et al., 2018), which helps in improving the primary productivity of paddy fields' water in IRFS. These processes increase C sequestration, while improving better gas and nutrient exchange (Wei et al., 2019). Furthermore, the introduction of fish into paddy fields has been found to address several environmental management issues, including weed and pest control (Stadlinger et al., 2018; de Sousa et al., 2012). IRFS can also reduce CO₂, CH₄, and N₂O emissions from paddy fields (Feng et al., 2021; Datta et al., 2009; Frei et al., 2007; Wang et al., 2024; Cui et al., 2023; Bashir et al., 2020; Paramesh et al., 2022; Sun et al., 2021). However, the quality (species/variety) and quantity of rice and fish determine how well synergy functions (Hu et al., 2022). Fish and aquatic animals' feeding behavior, and other morphological and physiological

behavior, play a crucial role (Clasen et al., 2018; Fan et al., 2017). However, creating efficient synergy in IRFS requires the appropriate biomass and diversity of aquatic animals (Jia et al., 2023; Lv et al., 2020; Yang et al., 2022; Chand et al., 2006; Zhang et al., 2024).

3.1.7. Economic diversification

Recent studies indicate integrated farming systems can balance the prudent use of resources with significant economic benefits for farmers (Das et al., 2019, 2014). This is particularly true for IRFS-based interventions that require minimal labor and costs to produce indigenous rice and fish varieties with strong local demand (Li et al., 2021; Lu and Li 2006). Additionally, the use of genetically modified or hybrid fish and rice varieties in IRFS has fostered economic diversification away from RMS, yielding reasonable profits and enhanced livelihood opportunities (Inayat et al., 2023; Saikia 2024). However, in IRFS, enhanced plant and aquatic animal biodiversity could lead to economic sustainability by improving primary productivity, allowing enhanced biomass. IRFS enhance the dietary diversity of commercially important aquatic organisms, creating better economic opportunities than RMS (Li et al., 2021; Ahmed and Garnett 2011). Furthermore, researchers discovered that IRFS balance enrichment of beneficial organisms (such as soil microorganisms, planktons, aquatic vertebrates, and invertebrates), maintaining stability and increasing yield and economic gain (Ahmed et al., 2021).

3.1.8. Co-creation of knowledge

One important aspect of the consolidated AE principles is that, although they are stated broadly, they are implemented locally. In practice, agroecological practices are appropriate according to the specific conditions of each place (Sinclair et al., 2019). In this sense, the co-creation of knowledge is crucial for establishing locally adapted practices. The practices embrace fair participation of a variety of stakeholders, especially farmers with their local knowledge (Sinclair et al., 2019). Improving farming practices to address pressing challenges is a key area of knowledge co-creation (Triste et al., 2018). Productivity, financial benefit, and local demand for fish and rice motivate integrated rice fish system-based knowledge co-creation that can support their adoption (Syaukat and Julistia, 2019; Niyaki and Allahyari, 2011; Bosma et al., 2012; Bai et al., 2024; Ahmed and Garnett, 2011; Islam et al., 2015). Integrated rice fish system-based knowledge co-creation also improves when stakeholders develop a precise understanding of existing scenarios (technical and social) (Feng et al., 2016; Sinhababu and Poonam, 2022). Enhancements in productivity, financial gains, and local demand for specific rice and fish varieties have been shown to hasten the adoption of integrated rice fish system-based farming practices (Islam et al., 2015), where knowledge transfer between farmers may be heightened (Liu et al., 2016).

3.1.9. Social values and diets

Natural resource availability influences the human diet and is, in turn, influenced by topography, seasonality, and climate (Muhammad and Khan 2021). Their significant role in shaping a particular landscape-based agroecosystem is undeniable (Altieri et al., 2012). The natural resource context can influence local diet and nutrition (Stratton et al., 2020). IRFS implementation is also subject to these influencing factors; dietary preferences for rice and fish largely rely on their local availability and/or climatic resilience, which may vary with the environmental conditions (e.g., hilly terrain, flood plains, etc.) (Berg et al., 2012; Nguyen et al., 2018). The long-term practice of IRFS can also influence local diet and livelihoods through indigenous, high-yielding rice and fish varieties (Sathoria and Roy 2022; Sinhababu and Poonam 2022). Outperforming RMS in resource use, diversity, productivity, and the quality and quantity of the food produced, IRFS significantly contribute to increased food production (Frei and Becker, 2005; Ahmed and Garnett, 2011). Mirhaj et al. (2013) documented a significant rise in incomes and sustainable economic growth among farming households through rice fish and prawn farming in southeast Bangladesh. In India, the positive role of IRFS in offering a

local diet and economic growth could be seen in Ziro Valley, Arunachal Pradesh (Samaddar et al., 2025b). IRFS have gained recognition for providing FNS (Garaway et al., 2013).

3.1.10. Fairness

The literature lacks information about how engaging relevant stakeholders in IRFS-based food systems affects livelihoods. However, studies suggest that IRFS primarily rely on direct links between producers and consumers, succeeding when extensive practices allow direct community access to food products (Freed et al., 2020a; Sathoria and Roy, 2022; Belton et al., 2020). With more commercial approaches and increased production levels of rice and fish, the entry of intermediaries could be found to create some adverse effects on IRFS-based food system networks, such as price increases in Bangladesh (Sunny et al., 2021). More evidence is required to be generated to develop a pertinent database for those and case studies are needed to understand how local demand and marketing strategies—such as the community’s indirect access to fish and rice due to the involvement of intermediaries in the food chain—could challenge fairness in an IRFS-based food system.

3.1.11. Connectivity

Among AE principles, researchers describe connectivity in terms of closeness and confidence between producers and consumers (HPLE, 2019). The primary drivers of connectivity in IRFS were identified as: access to adequate landscapes; access to necessary agricultural resources (fish, rice fields, water, etc.); availability of inputs; local demand for rice and fish; and presence of local marketplaces, which are regulated by a local diet- and product-based value chain (rice and fish). The interdependence of each of these factors influences FNS and the economic growth outcomes of IRFS (Wang and Gao 2017; Freed et al., 2020a; Ray and Chakraborty 2021; Sathoria and Roy 2022).

3.1.12. Land and natural resource governance

Sustainable land management can mitigate the effects of climate change. Land can act as a carbon sink, absorbing carbon dioxide and storing carbon in woody biomass and soils (Norbu et al., 2008). Integrated rice fish farming system can be an effective model for the governance of land and natural resources (Frei and Becker, 2005; Rautaray, 2021). Ahmed and Turchini (2021) predict that IRFS could increase global fish and rice production by 27%. Governance by smallholder or landless rural communities exemplifies one such model, managing natural fisheries resources within paddy fields and using these resources for FNS and livelihoods (Freed et al., 2020b; Shankar et al., 2004). Less sustainable models include land modification and using natural resources related to fish farming, and the creation of advanced irrigation facilities in paddy fields (Kumar et al., 2023; Sathoria and Roy, 2022). Climate change and the depletion of indigenous resources challenge efforts to manage natural resources and land dependent on IRFS (Berg et al., 2017; Cochard et al., 2014). Therefore, promoting climate-resilient resource management policies for IRFS should support high-yielding and genetically updated varieties of rice and fish, along with required land modifications (Mridha et al., 2014; Uddin et al., 2021; Ren et al., 2018).

3.1.13. Stakeholder Participation

FNS, land resource management, traditional and cultural aesthetics, productivity, demand, and profitability compel stakeholders to participate in a food system (Bhattacharyya et al., 2020; Hebsale Mallappa and Pathak, 2023; Altieri 2018; Myeni et al., 2024). These drivers of participation can be found in IRFS (Das et al., 2013; Liu et al., 2017). The involvement of stakeholders—market participants, input suppliers, performance evaluators, information developers, policy advisers, researchers, and decision-makers—has shaped IRFS-based practices in many countries. These actors address FNS (Ahmed and Garnett, 2011), livelihoods (Joffre et al., 2021), and climate-change issues (Ahmed et al., 2014). IRFS could increase efficiency through local adaptive management, capacity building, knowledge acquisition, key inputs, funding, and infrastructure development, all of which require multiple stakeholders’ participation (Das et al., 2013; Freed et al., 2020b). Overall, we found that 23

IRFS attributes are directly related to 13 AE principles. Similarly, 29 secondary attributes have the potential to influence 23 primary attributes, demonstrating an indirect impact on AE principles. Figure 3 illustrates these findings.

3.2. Alignment of agroecological IRFS with addressing FNS

FNS researchers increasingly focus their attention on multidimensional aspects of food systems (Kerr et al., 2021). Measuring the food system's (direct and indirect) ability to address FNS using an AE principle-based framework would be crucial during the evaluation process (Wezel et al., 2020). In the current study, we examined the IRFS-based food system's influence on FNS, taking into account the primary attributes and related principles that directly affect FNS. Secondary attributes can exert an indirect influence by boosting system productivity or enhancing societal economic gain. While other AE principles were not explicitly related to FNS, they showed a strong positive influence on the overall productivity of IRFS (Figure 5).

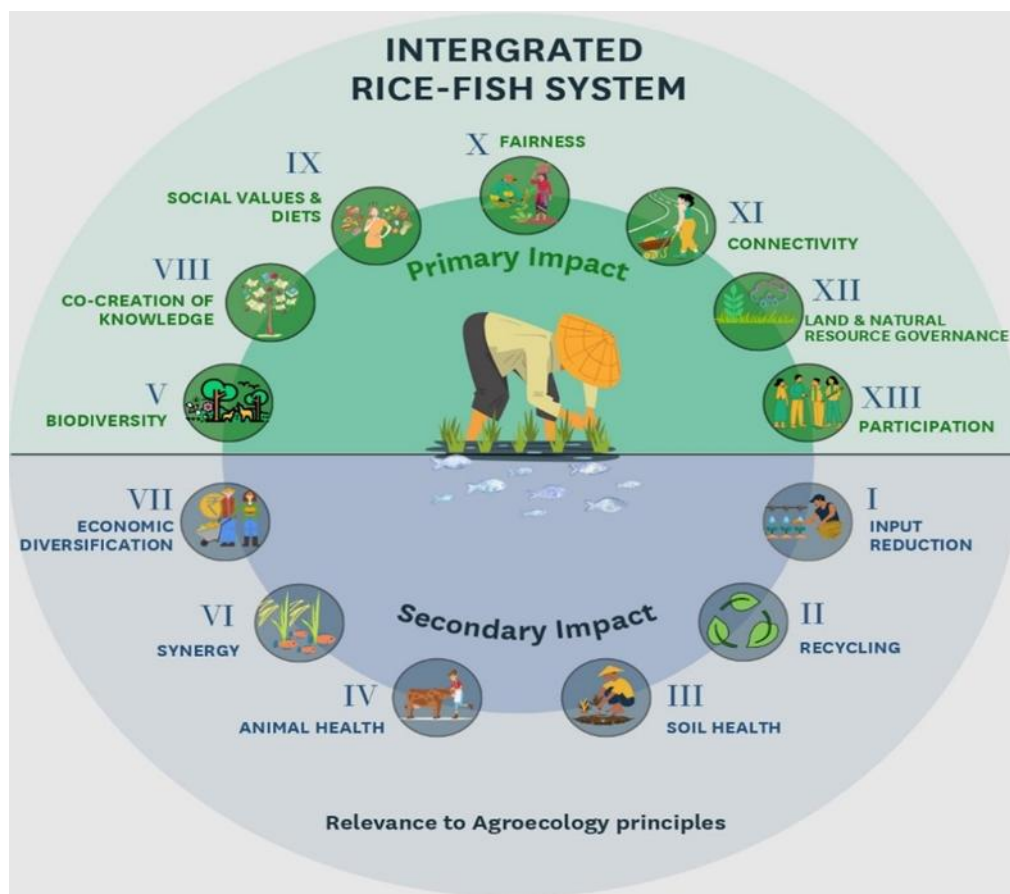


Figure 5: AE principles addressing FNS in an IRFS

Empirical evidence on connectivity suggests that the traditionally adopted IRFS helps maintain linkages among producers and consumers. Connectivity enhances accessibility of locally preferred indigenous rice and fish either through local marketplaces or at farm gates (Freed et al., 2020a,b; Ray and Chakraborty, 2021). IRFS can address FNS through traditionally inherited knowledge for securing dietary carbohydrates, protein, and micronutrients (Bashir et al., 2020; Fiedler et al., 2016; Freed et al., 2020a,b), often more efficiently than RMS (Ahmed and Turchini, 2021). Researchers found that the abundance of natural aquatic biodiversity in paddy fields ensured FNS through superior diet quality (Halwart 2008; Berg et al., 2012). IRFS biodiversity directly influenced FNS (Freed et al., 2020b). Moreover, indirect roles of economic diversification and input reduction were found to positively influence economic gain as compared to RMS (Frei and Becker 2005; Ahmed and

Turchini 2021; Sinhababu and Poonam 2022; Mohanty 2010; Berg et al., 2023). Enhanced income generation can improve access to food in rural communities and serve as a key positive influencer to FNS (Islam et al., 2015; Wezel et al., 2020). Research has indicated that involving relevant stakeholders from various backgrounds can enhance risk management through IRFS-based practices (Laborte et al., 2012). Identifying obstacles and motivators can aid in designing sustainable strategies for edible rice and fish production (Samaddar et al., 2025b). Such efforts were helpful for policy development (Dey et al., 2013; Duncan et al., 2021). The primary role of market players was found to enhance demand and availability of IRFS-based food products locally (Ababouch et al., 2023). Relevant stakeholders' (producers and consumers) participation and access to IRFS-based food products together determined accountability for FNS (Sunny et al., 2021). Empirical evidence indicates that the integrated availability of rice and fish through rice-fish culture systems can substantially decrease rural communities' reliance on commercially sourced rice and fish products (Samaddar et al., 2025b). Besides supporting household FNS, such a situation allows them to trade their produce with neighbors or make IRFS products more accessible by directly selling to the buyers at farmgate prices, which could significantly impact FNS, with the active participation of smallholders and access-related fairness in the IRFS-based food system (Joffre et al., 2021; Tilley et al., 2024). As a result, researchers found that the co-creation of knowledge can create primary impacts on FNS through connectivity (Freed et al., 2020b), social movements and diet (Ahmed and Garnett 2011), participation (de Silva et al., 2016), land and natural resource governance (Samaddar et al., 2025b), fairness (Fullbrook 2013), and biodiversity (Berg et al., 2012). Each of these principles has been shown to enhance communities' direct access to edible IRFS-based food products. Secondary impacts of economic diversification and input reduction are seen in IRFS practitioners' increased ability to purchase food when their financial situation improves.

3.3. IRFS in Eastern India

Even though IRFS-based evidence has been around for many decades in Eastern India (Kumar et al., 2011), no attempt has ever been made to characterize the AE quality of these systems. We found several scoping studies and preliminary reports, from which we were able to identify five distinct IRFS in Eastern India. These studies had documented empirical findings on the IRFS adherence to AE principles, as well as their contribution to FNS. We determined the indicators relevant to the AE principles. Table 2 summarizes the total number of AE principles, cultivable rice and fish varieties, and food production efficiency of selected IRFS. In Figure 6, the alignment of IRFS in Eastern India with AE principles has been illustrated.

Location	Purpose	Rice varieties	Targeted fish varieties	Average Annual Rice productivity (kg/ha)	Average Annual Fish productivity (kg/ha)	Number of Agroecological principles linked To FNS
Ziro valley, Lower Subansiri district, Arunachal Pradesh	Food, nutritional security and livelihood (FNSL)	<i>Oryza sativa</i>	<i>Cyprinus carpio</i>	3-4 t/ha	0.5 t/ha	10
Kikuma village, Phek district, Nagaland	Food and nutritional security (FNS)	<i>Oryza sativa</i>	<i>Cyprinus carpio</i> , <i>Channa striatus</i> , <i>Viviparus bengalensis</i> and <i>Pomacea canaliculata</i>	3-3.5 ton / ha	0.06 – 0.075 t/ha	7
Flood plain based IRFS of (Brahmaputra, Barak Valleys covering Cachhar Barpeta and Nagaon district) of Assam	FNSL	<i>Oryza sativa</i>	Wild captured fishes and other aquatic organisms	-	0.003-0.45 t/ha	9
Purba Medinipur district, West Bengal	FNSL	<i>Oryza sativa</i>	Wild captured fishes and prawns	2.0 - 2.5 t/ ha.	0.2-0.25 t/ha	6
South 24 Parganas district, West Bengal	FNSL	<i>Oryza sativa</i>	Wild captured fish and prawns	1.0 t/ha	0.1–0.2 t/ha	7

Table 2: Alignment of AE principles with selective IRFS of Eastern India

Agroecological Principles	Ziro valley	Kikuma village	Assam's flood plain zones	Purba Medinipur	South 24 Parganas
i	Yellow				
ii	Light Blue		Light Blue		
iii		Green			
iv					
v		Orange			
vi	Grey				
vii	Pink		Pink		
viii	Light Green				
ix	Yellow				Yellow
x	Red				
xi	Blue		Blue		Blue
xii	Purple				
xiii	Black				

Figure 6: Alignment of agroecological principles with selective IRFS of Eastern India.

3.3.1. Characterization of selected IRFS

IRFS of the Ziro Valley, Arunachal Pradesh: The Apatani tribe has been practicing IRFS here for over five decades. Ingrained in their culture and traditions, they cultivate and produce preferred food items with a positive influence on local FNS (Samaddar et al., 2025b) (ix).¹ The community extensively embraced a method that local government officials co-created and promoted to increase paddy field production and financial profit. The effort includes a notable role for women family members as farm operators (viii, xiii) (Saikia, 2024). By introducing indigenous rice varieties, in addition to common carp, implementing IRFS in nearly all Ziro Valley's suitable areas (592 ha) has had a major positive impact on social values and diet quality (ix). Furthermore, the sale of excess produce has created a diversified economy, demonstrating fair trade through direct sales. Producers, sellers, and consumers—either at the farm gate or in the Hapoli neighborhood market—connect within a short supply chain (vii, x, xi) (Samaddar et al., 2025b,a).

All farming ingredients, except fish seeds, are readily available locally. The farming methods largely depend on recycling organic farm by-products, such as manures and paddy straws. They demonstrate systematic management of land and natural resources through well-designed irrigation systems. This approach uses locally accessible natural resources, such as water and agricultural by-products, without the need for additional external farming inputs (i, ii, xii), except for the procurement of common carp fingerlings from vendors in neighboring states (xiii) (Saikia and Das, 2015). Beneficial effects on water quality parameters have been documented (vi) (Saikia and Das, 2009). Consequently, the synergies between the key elements of the IRFS-based ecosystem—rice, fish, soil, and water—cannot be discounted. They have been shown to enhance paddy field output in addition to fish as a secondary crop (vi) (Saikia, 2024). However, information on biodiversity (micro and macro level), soil, and animal health is still missing.

IRFS of Kikuma village, Nagaland: The Chakhesang/Zabo tribe adopted 957.9 ha of land for integrated farming with traditional techniques (viii, xiii), with IRFS as an essential component for FNS (Das et al., 2021; Das, 2024). Here, superior land modifications that are in line with nature are evident; they are used for diversified crop raising with well-arranged, traditionally built irrigation facilities (xii). Native and non-native fish, as well as native tall indigenous rice varieties, have been cultivated in IRFS (v) by maintaining the fertility of the soil and by recycling readily available natural byproducts for microbial health (Das et al., 2012; Modak et al., 2024). Except for imported non-native fish fingerlings (xi), this community relies on local resources. Furthermore, the produced crops are entirely used by the individual family for household consumption (ix) (Sathoria and Roy, 2022), promoting economic self-reliance and fairness.

Diversified IRFS of Assam: The Brahmaputra and Barak Valleys in Assam are home to deepwater indigenous tall rice varieties (Sali and Aman) and field-based capture fishing. Traditionally, IRFS in these regions are primarily used for rural households' FNS and secondarily for income generation (ix). Community-based IRFS management, with the remarkable participation of tribal women who sell a variety of indigenous fish species for local consumption, is prominent (xi, xiii). The region's enormous aquatic biodiversity has been identified as a key factor in economic diversification (v, vii) (Das, 2018). Minor land modifications, such as the placement of fish traps, trenches, and ditches, along with the recycling of natural by-products to maintain land fertility, are common practices (iii, xii).

Additionally, semi-intensive carp cultivation in paddy fields, using seeds either locally grown or imported from neighboring states, combined with minimal use of commercial fertilizers and fish feeds, has been co-created to enhance net economic returns by 117% (Bhuyan et al., 2018) (ii, viii). Despite these promising outcomes, inadequate evidence limits our ability to fully explain the fairness of such participatory economic ventures.

¹ the Roman numeral used for the relevant AE principle is provided after each indicative trait of IRFS

IRFS of Moina, West Bengal: Along the flood plains of the Kangsabati River in the Moina development block, the community mode of IRFS operation has been documented (xiii). This floodplain system allows monsoon rain or floodwater to enter high-diked and well-guarded paddy fields through artificial irrigation canals from local rivers. These fields, equipped with indigenous fish traps and fencing, support extensive or semi-intensive aquaculture, integrating traditional and scientific knowledge (viii, xii). This system predominantly relies on natural resources, such as river water and fish seed, enabling the cultivation of wild-stocked riverine fish and prawn varieties, occasionally supplemented with locally purchased carp species and semi-intensive management practices (v). This approach remains operational over a vast area and has influenced many to adopt it for their daily nutritional needs, ensuring FNS and economic gain through the sale of rice and fish (vii, ix) (Bhaumik and Sharma, 2012). However, there is no available information on marketing strategies, connectivity, or product-based value chain facilities.

IRFS of Sundarban, West Bengal: This region possesses an extensive and alternative IRFS system spread over an area of about 30,000 ha, used for the local diet, serving as an important livelihood option through community farming (ix). Traditionally, farmers build large, impounded water bodies (Bheri), flooded with estuarine brackish water. They cultivate naturally caught diverse fish and prawns, in rotation with salt-tolerant rice production during rabi season (season runs from October to April) (Bunting et al., 2017; Poonam et al., 2019) (v, xii). Ghosh and Mistri (2020) found that encouraging semi-intensive, management-based, scientifically upgraded system models—co-created by combining horticulture with IRFS—enhanced local income and food availability and compelled adoption by 44% of rice farmers at Gosaba block, Sundarbans (viii). Evidence suggests a strong role of such practices over FNS and livelihoods (xiii), where commercially important diverse aquatic food products (fish, shrimp, crabs, etc.) are mostly exported through standardized marketing channels (vii, xi) (Ghoshal et al., 2019). However, accurate indicators in line with other AE principles are still unknown.

Overall, according to empirical evidence, Ziro Valley's rice fish system addressed a total of 10 AE principles. Assam IRFS addressed nine. The IRFS in the South 24 Parganas district of West Bengal addressed seven. The IRFS in Kikuma village in Nagaland and the Moyna region of West Bengal have addressed six AE principles each.

Other potential areas in Eastern India: The Kom community in the Indian state of Manipur, India, practiced IRFS for both domestic and commercial purposes (Mylliemngap, 2021). Here, middle-aged (36 to 50 years) family members hold one acre of land in a system that generates employment and ensures FNS (Haobijam et al., 2016). In Mizoram state, IRFS—practiced by the local community with traditional knowledge—produce 100 kg/ha of fish annually (Hussan et al., 2018). In some regions of Meghalaya state and Ukhrul district of Manipur, common carp-based IRFS models are implemented (Das, 2018; Deepitha et al., 2019). Farmers in the East Godavari district of Andhra Pradesh state were reported to have extensive IRFS-based practices, producing 3 to 6 kg/ha of fish annually, apart from standard paddy production (Deepitha et al., 2019). APCNF pilots natural farming methods based on IRFS in Andhra Pradesh (Samaddar et al., 2024). Dey et al. (2019) identified the potential for rice-fish farming systems in Bihar's low-lying areas, however the lack of documentation regarding AE traits in Bihar prevents thorough evaluation of this IRFS potential.

3.3.2. Constraints and challenges in implementing an IRFS-based agroecological transition in Eastern India.

Comprehending the hurdles still present in IRFS systems and the difficulties in relevant AE transitions in Eastern India has received special attention. Through the literature search, we identified the seven most common constraints, summarized below.

- (1) Low productivity of rice and fish: Particularly in extensive IRFS practices, low productivity remains a primary constraint, calling for research and innovation to enhance efficiency (Das, 2018; Sathoria and Roy, 2022).
- (2) Initial investment costs and fund constraints: Challenges include the high initial investment required for land reformation, financial constraints among potential farmers, and operational costs for aquaculture management (Bashir et al., 2020; Dey et al., 2013).
- (3) Natural disasters: Flood-prone areas in Assam and the coastal belts of the Sundarbans are vulnerable to natural disasters, posing significant challenges to IRFS sustainability (Gogoi et al., 2015; Bunting et al., 2017; Mandal et al., 2021).
- (4) Challenges in hilly terrain: The northeast's hilly terrain presents challenges such as reduced fish productivity due to inefficient management practices, lack of specialized extension services for IRFS, input shortages, and logistical challenges hindering scientific upgrades of conventional IRFS (Bania et al., 2024).
- (5) Loss of indigenous fish varieties: Rapid habitat loss of small indigenous fish species in paddy fields, exacerbated by high stocking of new or invasive species, poses a significant threat (Sathoria and Roy, 2022).
- (6) Environmental impacts of inputs: Non-ideal use of fertilizers and supplementary feeds in Eastern Indian states has negative impacts on soil and water quality, posing environmental challenges (Tripathi et al., 2020).
- (7) Land-use change: Increasing conversion of rice fields to aquaculture ponds in states like West Bengal, Odisha, and Andhra Pradesh threatens the sustainability of IRFS (Belton et al., 2017; Goswami and Ghosal, 2022).

Empirical evidence suggests that these seven major constraints or challenges have been associated with Eastern Indian IRFS. However, our results indicate that problems could be region-specific and vary with context. Addressing these constraints requires integrated approaches that combine technological innovation, policy support, community engagement, and sustainable management practices to promote the resilience and viability of IRFS-based AE systems in Eastern India.

3.3.3. Strategies implemented to scale-up adoption

Considering the constraints and challenges faced by IRFS, national policymakers (e.g., Indian Council of Agricultural Research (ICAR) National Mission on Natural Farming (NMNF)) and international research for development agencies (Food and Agriculture Organisation of the United Nations (FAO), CGIAR) created workable plans for maximizing IRFS at the farmer level in Eastern India. However, these plans never mentioned or considered AE, though their approach seems aligned with AE (Sathoria and Roy, 2022). Measures have been suggested that promote scientific understanding among farmers and build capacity to consider IRFS over rice monoculture practices (Bashir et al., 2020; Das, 2018, Anyango et al 2025). ICAR-NRRI and the Government of India have co-developed and promoted standardized, protocol-based integrated models. These models address multidimensional aspects of farming systems, like productivity improvement, income generation, sustaining biodiversity, synergistic use of resources, improvement in greenhouse gas emissions, and community participation, etc., by (Sinhababu and Poonam, 2022). Other noticeable initiatives have been taken by prominent Indian government agencies, like the National Bank for Agriculture and Rural Development (NABARD) and the Department of Science and Technology (DST), which

have funded pilot projects to promote semi-intensive rice-fish systems in Odisha, West Bengal, and Arunachal Pradesh (Sathoria and Roy, 2022). Some direct interventions by both governments also promoted IRFS. These efforts provided necessary financial and input support to small and marginal farmers in several Eastern Indian states under different schemes like the Rashtriya Krishi Vikash Yojana, the National Horticulture Mission, and the Pradhan Mantri Matsya Sampada Yojana (Poonam et al., 2019; Nayak et al., 2020). The Indian government now primarily focuses on improving technical skills, efficiency, and farming communities' participation (Sathoria and Roy, 2022). Nonetheless, empirical evidence indicates that local solutions must be developed to address the challenges or constraints that are region-specific.

4. Discussion

4.1. How IRFS qualities address agroecological transition

Initially, this review clarified how AE principles could have an impact on unique IRFS-based food systems during an AE transition. Following the consolidation of pertinent evidence, the results showed that IRFS possesses a total of 52 attributes that primarily or secondarily generate impact over the intended AE transitions. The review also confirmed that IRFS could demonstrate 13 agroecological principles. Among distinct components (soil, water, rice, and fish), synergy emerges as a crucial AE principle that integrates other principles within IRFS (Wezel et al., 2020). Fish contribute to developing a more self-sufficient, productive, and sustainable system compared to RMS. IRFS can positively influence AE principles like biodiversity, input reduction, economic diversification, social values, and diet. Among the most important findings, we observed that connectivity among pertinent stakeholders (e.g., Local Enterprises and communities, Agricultural Workers, Consumers, Policy Makers) would be crucial for better management of natural resources. For example, Skokanova et al., (2020) found similar phenomena, where connectivity fostered conventional agriculture across an entire landscape.

Finally, leveraging the regional spread of farming practices (here IRFS) might be influenced by the co-creation of knowledge and the participation of farming communities (van Ewijk and Ros-Tonen, 2021). Nevertheless, additional empirical research is required to substantiate the efficacy of IRFS in contributing to a more comprehensive understanding of AE principles and their associated requirements (Hou et al., 2024). To understand how aquatic animals affect IRFS ecosystems, it's important to consider their behavior within the AE system.

4.2. Agroecological IRFS addressing FNS

The findings suggest that achieving FNS can be facilitated by synergizing 13 AE principles in IRFS. The impact of AE transitions on FNS can vary, depending on the specific types of IRFS and the demand dynamics for food products. Among seven important primary impact-creating AE principles, biodiversity, land and natural resource governance, and participation may be the most important (Ghosh and Mistri, 2020; Sinhababu and Poonam, 2022). However, achieving fairness in the food system hinges on sufficient food availability and rural community access to food (McGarraghy et al., 2022). Creating secondary impacts to FNS could be achieved with economic diversification (Upadhyay and Singh, 2013). Recent studies on IRFS again validate that agricultural components, such as livestock, horticulture, or agriculture, and the co-creation of knowledge can improve FNS (Ghosh and Mistri, 2020; Sinhababu and Poonam, 2022). In addition, the role of ecological attributes on FNS cannot be ruled out, due to their secondary influences. However, achieving ideal conditions involves maintaining an optimal balance of suitable organisms for IRFS (Samaddar et al., 2025b).

4.3. Eastern India perspective

Among Eastern Indian IRFS, the Arunachal Pradesh system shows the most AE characteristics, where synergistic impacts of 10 distinct AE principles are related to impact on FNS. Participation and co-creation play significant roles in creating direct positive impacts through effective land and natural resource governance initiatives. The Arunachal Pradesh government spearheads and scales up these efforts by integrating common carp in paddy fields (Samaddar et al., 2025a). Subsequent advances in ecological understanding further bolster the AE knowledge base. In Nagaland, while traditional knowledge contributes to co-creation, the lack of empirical evidence on ecological processes hinders a comprehensive understanding of the AE transition. In Assam and West Bengal's capture fisheries-based IRFS, biodiversity and local community participation emerge as critical factors contributing to FNS. The discontinuation of fishery resources use in paddy fields highlights key AE characteristics, including diminished community participation, reduced dietary diversity, and declining reliance on indigenous rice and fish varieties. However, challenges persist, particularly concerning the commercial viability of AE practices. Resource-poor farmers,

driven by economic goals, often prioritize productivity enhancement and income generation over supporting local food systems, ecology, and community engagement (Van der Ploeg et al., 2019). The integration of more farming components in places like Gosaba in West Bengal indicates a commercially successful AE transition with positive impacts on FNS, underscoring the validity of co-creation in accelerating AE transitions.

Existing challenges in the system indicate the need to evaluate existing strategies and develop supportive policies by considering three main areas: environment, economy, and food safety. To deal with these issues, 13 principle-based AE frameworks would be ideal (Kerr et al., 2021; Wezel et al., 2020). Furthermore, they would be essential to comprehend the capacity of any given ecosystem to fulfill the demand for chosen crop types, before putting any solutions into practice in the field (Mottet et al., 2020; Jacobi et al., 2018). Such an assessment may also allow the identification of potential zones for IRFS-dependent food systems. As the situation indicates, extension services might not yet be in place with a strategic, goal-oriented approach. This could limit IRFS adoption rates (Bashir et al., 2020). In this case, suggested protocols from regional, national, and international organizations could provide a roadmap. More attention may need to be paid to understanding factors responsible for farmers' behavioral changes (Nasiri et al., 2024). Stakeholders should employ mutual learning and understanding to consider the actual demand-based community-level strategies (Pfundtner-Heise et al., 2024). Additionally, as animal health and FNS are intimately related (Häsler et al., 2017), more urgent efforts must be made to comprehend how IRFS affects fish health in Eastern India. This will help to close the knowledge gap between policymakers and farmers, as well as speed up the AE transition. Similar strategies were found to be effective in some other countries for different farming types (Kerr et al., 2021).

4.4. Research Gaps and Priorities

Despite decades of practice, Integrated Rice–Fish Systems (IRFS) in Eastern India remain under-characterized and insufficiently integrated into agricultural and fisheries policy frameworks. While empirical evidence from Arunachal Pradesh, Nagaland, Assam, and West Bengal demonstrates that these systems adhere to six to ten agroecological principles and contribute to food and nutrition security (FNS), critical gaps persist. Ecological indicators such as soil and water quality, micro- and macro-biodiversity, and fish and animal health remain inadequately documented. Social and governance dimensions—including gender roles, equity, community participation, and local decision-making—are also poorly captured, limiting the ability to assess system resilience and fairness. At the policy level, extension services predominantly promote high-input monocultures and commercial aquaculture, leaving little institutional support for IRFS adoption and scaling. Monitoring frameworks rarely include agroecological or nutrition-sensitive indicators, preventing IRFS from being recognized as tools for sustainable food systems or malnutrition mitigation. Market and value-chain policies tend to prioritize export-oriented outputs, which can inadvertently marginalize local consumers and reduce equitable access to nutritious foods. Furthermore, IRFS are seldom integrated into climate adaptation or ecosystem service strategies, despite their potential for flood regulation, water recycling, and biodiversity conservation. To address these gaps, policies must explicitly recognize IRFS as agroecological models, implement monitoring frameworks that capture ecological and nutritional outcomes, reorient extension services toward participatory co-creation with farmers, support localized market and value chains, and embed IRFS into climate-smart and nutrition-sensitive agricultural strategies. Such measures would not only strengthen the sustainability and resilience of Eastern India's IRFS but also position them as globally relevant models for agroecological transitions.

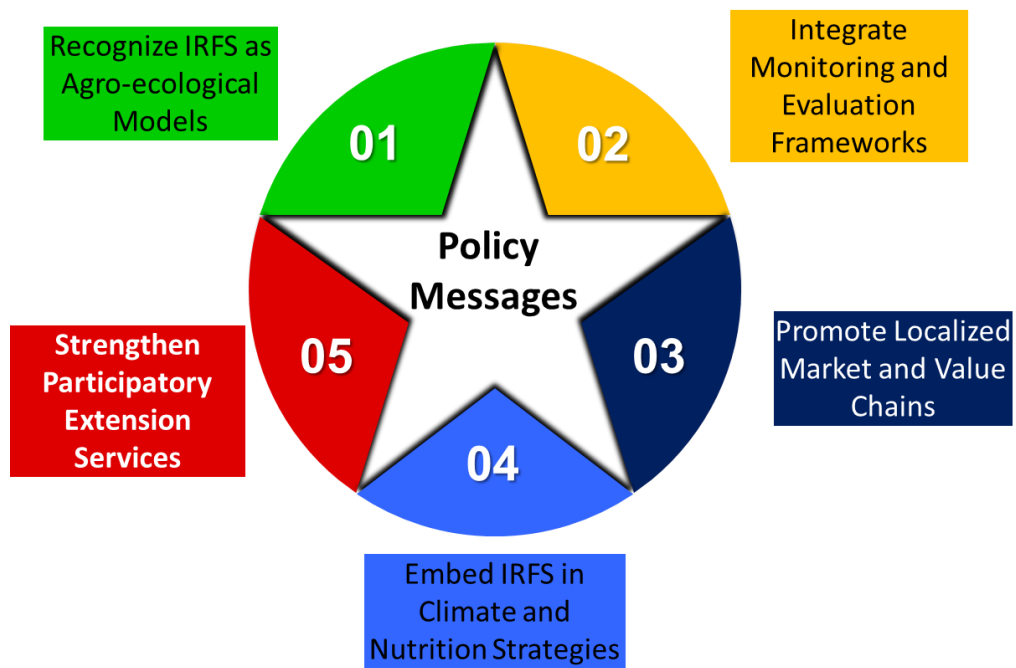


Figure 7: Key policy recommendation

5. Conclusion

The characteristics of IRFS can have an impact on AE principles (HPLE, 2019). Although experimental research on IRFS primarily focuses on ecological parameters and principles, the majority of field-level assessments have covered socioeconomic facets. There is insufficient data to assess the full potential of IRFS on FNS. However, limited evidence enables us to evaluate how IRFS might fit into AE frameworks for providing FNS. Ten major challenges in Eastern India have been identified in this review. Proposed farming strategies by government and non-government agencies must be evaluated using the AE framework to determine how well they address FNS and environmental sustainability. Research could also improve understanding of how the codesign process involves farmers and supports agencies. How do these processes influence the shift in farmers' practices, perspectives, and involvement in local innovation and knowledge creation? Before implementing any new AE technologies at the community level, this suggested research could inform future implementation. Additionally, the scope of this review could be expanded to evaluate whether AE IRFS deliver on their promise to provide farm workers with respectable and satisfying livelihoods, in addition to other facets of social sustainability. This assessment of IRFS and the potential benefits of their AE-relevant practices on FNS strengthens the arguments made recently on a worldwide scale for increased funding for AE research (HPLE, 2019). The benefits of natural farming movements (Willer et al., 2024), resilience enhancement (Sinclair et al., 2019), biodiversity conservation (De and Dwivedi 2024), and ecosystem services (Morri and Santolini 2021) are also supported by the review.

Future research could identify additional AE attributes to develop in order to enhance the contribution of Eastern Indian IRFS and their impacts on the FNS. Socioeconomic aspects of agroecology, including direct marketing, resolving social injustices, and managing land and natural resources, have received little attention in Eastern India. Furthermore, ecological indicators related to soil health, animal health, and synergy have received little consideration during co-design of food systems.

Author contributions

Ayan Samaddar: Writing original draft, data curation, conceptualisation, and literature search. **Subrata Saha:** Writing – review & editing, methodology, literature search. **Sonali Singh:** Writing – review & final editing. **Nilendu Basak:** writing – review & editing, literature search, **Rajib Majumder:** Writing – review & editing. **Sudharsan Malaiappan:** Methodology, review, and editing. **Neetha Shenoy:** writing – review & editing, literature search. **Shwu Jiau Teoh:** Methodology and resource mapping. **Arun Padiyar:** Resources, project administration, funding acquisition. **Sarah Freed:** Writing – original draft, validation, conceptualisation, supervision.

Financial disclosure: None reported.

Conflict of interest: The authors declare no potential conflict of interest.

References

- Ababouch, L., Nguyen, K.A.T., Castro de Souza, M., Fernandez-Polanco, J., 2023. Value chains and market access for aquaculture products. *Journal of the World Aquaculture Society* 54, 2, 527–553.
- Ahmed, N., Bunting, S.W., Rahman, S., Garforth, C.J., 2014. Community-based climate change adaptation strategies for integrated prawn–fish–rice farming in Bangladesh to promote social–ecological resilience. *Reviews in Aquaculture* 6, 1, 20–35.
- Ahmed, N., Garnett, S.T., 2011. Integrated rice–fish farming in Bangladesh: meeting the challenges of food security. *Food Security* 3, 81–92.
- Ahmed, N., Hornbuckle, J., Turchini, G.M., 2022. Blue–green water utilization in rice–fish cultivation towards sustainable food production. *Ambio* 51, 9, 1933–1948.
- Ahmed, N., Thompson, S., Hardy, B., Turchini, G.M., 2021. An ecosystem approach to wild rice–fish cultivation. *Reviews in fisheries science & aquaculture* 29, 4, 549–565.
- Ahmed, N., Turchini, G.M., 2021. The evolution of the blue–green revolution of rice–fish cultivation for sustainable food production. *Sustainability Science* 16, 4, 1375–1390.
- Ahmed, N., Zander, K.K., Garnett, S.T., 2011. Socioeconomic aspects of rice–fish farming in Bangladesh: opportunities, challenges and production efficiency. *Australian Journal of Agricultural and Resource Economics* 55, 2, 199–219.
- Altieri, M.A., 2018. *Agroecology: the science of sustainable agriculture*. CrC press.
- Altieri, M.A., Funes-Monzote, F.R., Petersen, P., 2012. Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. *Agronomy for sustainable development* 32, 1, 1–13.
- Anyango, B., Hou, V., Xu, H., Zhou, L., Thay, S., Wu, X. and Zhang, W., 2025. Investigating the resistance of rice–field fisheries to transition into rice–fish farming and pond aquaculture in Cambodia. *Aquaculture and Fisheries*.
- Arunrat, N., Sereenonchai, S., 2022. Assessing ecosystem services of rice–fish co–culture and rice monoculture in Thailand. *Agronomy* 12, 5, 1241.
- Asada, H., Yamane, Y., Deka, N., 2022. Environmental changes and rural livelihoods in Muktapur village, Kamrup district, Assam, India. In *Environmental Change in South Asia: Essays in Honor of Mohammed Taher*. Springer, pp. 51–69.
- Bai, Y., Chen, C., Li, X., Liu, M., 2024. Factors influencing the progressive adoption of integrated rice–fish systems by farmers and its relapse. *Agricultural Systems* 221, 104142.
- Bania, J.K., Nath, P.C., Nath, A.J., 2024. Challenges and opportunities in achieving food security in northeast India. *Food Security in a Developing World: Status, Challenges, and Opportunities* pp. 207–228.
- Bashir, M.A., Liu, J., Geng, Y., Wang, H., Pan, J., Zhang, D., Rehim, A., Aon, M., Liu, H., 2020. Co–culture of rice and aquatic animals: An integrated system to achieve production and environmental sustainability. *Journal of Cleaner Production* 249, 119310.
- Belton, B., Padiyar, A., Ravibabu, G., Rao, K.G., 2017. Boom and bust in Andhra Pradesh: Development and transformation in India’s domestic aquaculture value chain. *Aquaculture* 470, 196–206.
- Belton, S., Jamieson, M., Lawlis, T., 2020. Despite challenges food relief is a conduit to developing relationships, trust and enabling client food security and specialized support: A case study. *Journal of Hunger & Environmental Nutrition* 15, 3, 311–326.
- Berg, H., Berg, C., Nguyen, T.T., 2012. Integrated rice–fish farming: safeguarding biodiversity and ecosystem services for sustainable food production in the Mekong Delta. *Journal of Sustainable Agriculture* 36, 8, 859–872.
- Berg, H., Ekman Söderholm, A., Söderström, A.S., Tam, N.T., 2017. Recognizing wetland ecosystem services for sustainable rice farming in the Mekong Delta, Vietnam. *Sustainability Science* 12, 137–154.
- Berg, H., Lan, T.H.P., Tam, N.T., Trang, D.H., Van, P.H.T., Duc, H.N., Da, C.T., 2023. An ecological economic comparison between integrated rice–fish farming and rice monocultures with low and high dikes in the Mekong Delta, Vietnam. *Ambio* 52, 9, 1462–1474.
- Bhattacharyya, P., Pathak, H., Pal, S., Bhattacharyya, P., Pathak, H., Pal, S., 2020. Barriers to adaptation of climate–smart agriculture. *Climate Smart Agriculture: Concepts, Challenges, and Opportunities* pp. 155–167.

- Bhattacharyya, P., Sinhababu, D., Roy, K., Dash, P., Sahu, P., Dandapat, R., Neogi, S., Mohanty, S., 2013. Effect of fish species on methane and nitrous oxide emission in relation to soil C, N pools and enzymatic activities in rainfed shallow lowland rice-fish farming system. *Agriculture, ecosystems & environment* 176, 53–62.
- Bhattacharyya, S.S., Ros, G.H., Furtak, K., Iqbal, H.M., Parra-Saldívar, R., 2022. Soil carbon sequestration—an interplay between soil microbial community and soil organic matter dynamics. *Science of the Total Environment* 815, 152928.
- Bhaumik, U., Sharma, A., 2012. Seasonally flooded water bodies—a potential resource for rice-fish farming in West Bengal, India. *Fishing chimes* 32, 1, 110–116.
- Bhuyan, S., Ali, A., Laskar, B., Deka, M., Bora, M., Bharali, M., Chakraborty, M., Datta, H., Saharia, P., 2018. Fishery based integrated farming system: A promising way for doubling farmers' income in Nalbari district of Assam. *Journal of Community Mobilization and Sustainable Development* Vol. 13(2), 354-358.
- Bihari, P., Nayak, A., Gautam, P., Lal, B., Shahid, M., Raja, R., Tripathi, R., Bhattacharyya, P., Panda, B., Mohanty, S., et al., 2015. Long-term effect of rice-based farming systems on soil health. *Environmental Monitoring and Assessment* 187, 1–12.
- Billah, M.M., Uddin, M.K., Samad, M.Y., Hassan, M.Z., Anwar, M.P., Talukder, I., Shahjahan, M., Haque, A.N.A., 2020. Impact of feeding schedule on the growth performances of tilapia, common carp, and rice yield in an integrated rice-fish farming system. *Sustainability* 12, 20, 8658.
- Bisht, I.S., Rana, J.C., Jones, S., Estrada-Carmona, N., Yadav, R., 2022. Agroecological approach to farming for sustainable development: The Indian scenario. *Biodiversity of ecosystems* 107.
- Bosma, R.H., Nhan, D.K., Udo, H.M., Kaymak, U., 2012. Factors affecting farmers' adoption of integrated rice-fish farming systems in the Mekong Delta, Vietnam. *Reviews in Aquaculture* 4, 3, 178–190.
- Brahmanand, P., Ghosh, B., Sahoo, N., 2009. Effect of organic and inorganic sources of nitrogen on productivity of rice in rice-fish farming system. *Archives of Agronomy and Soil Science* 55, 6, 663–670.
- Bunting, S.W., Kundu, N., Ahmed, N., 2017. Evaluating the contribution of diversified shrimp-rice agroecosystems in Bangladesh and west Bengal, India to social-ecological resilience. *Ocean & Coastal Management* 148, 63–74.
- Chand, B., Goswami, A., Biswas, P., Biswas, P., Patra, B., 2006. Effects of stocking levels of ducks on production of Indian major carps in village ponds under duckfish integrated system in west Bengal state of India. *Growth* 200, D300, D400.
- Chandramouli, C., 2011. Census of India 2011: rural urban distribution of population (provisional population totals). Indian Ministry of Home Affairs, new delhi. http://censusindia.gov.in/2011-prov-results/paper2/data_files/india/rural_urban_2011.pdf. accessed 4, 20, 12.
- Chen, B., Guo, L., Tang, J., Li, Y., Li, C., 2024. Comprehensive impacts of different integrated rice-animal co-culture systems on rice yield, nitrogen fertilizer partial factor productivity and nitrogen losses: A global meta-analysis. *Science of The Total Environment* 915, 169994.
- Cheng, X., Li, F., Kumilamba, G., Liao, J., Cao, J., Sun, J., Liu, Q., 2023. Transcriptome analysis in hepatopancreases reveals the response of domesticated common carp to a high-temperature environment in the agricultural heritage rice-fish system. *Frontiers in Physiology* 14, 1294729.
- Cheng, X., Li, F., Lu, J., Wen, Y., Li, Z., Liao, J., Cao, J., He, X., Sun, J., Liu, Q., 2024. Transcriptome analysis in gill reveals the adaptive mechanism of domesticated common carp to the high temperature in shallow rice paddies. *Aquaculture* 578, 740107.
- Clasen, B., Loro, V.L., Murussi, C.R., Tiecher, T.L., Moraes, B., Zanella, R., 2018. Bioaccumulation and oxidative stress caused by pesticides in *Cyprinus carpio* reared in a rice-fish system. *Science of the total environment* 626, 737–743.
- Cochard, R., Maneepitak, S., Kumar, P., 2014. Aquatic faunal abundance and diversity in relation to synthetic and natural pesticide applications in rice fields of central Thailand. *International Journal of Biodiversity Science, Ecosystem Services & Management* 10, 2, 157–173.
- Cui, J., Liu, H., Wang, H., Wu, S., Bashir, M.A., Reis, S., Sun, Q., Xu, J., Gu, B., 2023. Rice-animal co-culture systems benefit global sustainable intensification. *Earth's Future* 11, 2, e2022EF002984.
- D'Annolfo, R., Gemmill-Herren, B., Graeub, B., Garibaldi, L.A., 2017. A review of social and economic performance of agroecology. *International Journal of Agricultural Sustainability* 15, 6, 632–644.

- Das, A., Datta, D., Samajdar, T., Idapuganti, R.G., Islam, M., Choudhury, B.U., Mohapatra, K.P., Layek, J., Babu, S., Yadav, G.S., 2021. Livelihood security of small holder farmers in eastern Himalayas, India: Pond based integrated farming system a sustainable approach. *Current Research in Environmental Sustainability* 3, 100076.
- Das, A., Layek, J., Ramkrushna, G., Babu, S., Devi, M.T., Dey, U., Suting, D., Yadav, G.S., Lyngdoh, D.B.D., Prakash, N., 2019. Integrated organic farming system: An innovative approach for enhancing productivity and income of farmers in north eastern hill region of India. *Indian Journal of Agricultural Sciences* 89, 8, 1267–72.
- Das, A., Munda, G., Azad Thakur, N., Yadav, R., Ghosh, P., Ngachan, S., Bujarbaruah, K., Lal, B., Das, S., Mahapatra, M., et al., 2014. Rainwater harvesting and integrated development of agri-horti-livestock-cum-pisciculture in high altitudes for livelihood of tribal farmers. *Indian J. Agric. Sci* 84, 5, 643–649.
- Das, A., Munda, G., Thakur, N.A., Lal, B., Ghosh, P., Ngachan, S., Bujarbaruah, K., Yadav, R., Mahapatra, B., Das, S., et al., 2013. Integrated agricultural development in high-altitude tribal areas: a participatory watershed programme in the east Indian Himalaya. *Outlook on AGRICULTURE* 42, 2, 141–144.
- Das, A., Ramkrushna, G., Choudhury, B., Munda, G., Patel, D., Ngachan, S., Ghosh, P., Tripathi, A., Das, S., Kumar, M., 2012. Natural resource conservation through indigenous farming systems: Wisdom alive in North East India. *Indian Journal of Traditional Knowledge*. Vol. 11(3), July 2012, pp. 505–513
- Das, D., 2018. Farming of fishes in ricefields of northeast India: A review. *Coldwater Fisheries Society of India* 1, 1, 27–41.
- Das, N.K., 2024. Ecological knowledge and sustainable farming practices among the naga tribes in northeast India: A reappraisal of their cosmological worldview. In *Environmental and Ecological Sustainability Through Indigenous Traditions: Perspectives from the Global South*. Springer, pp. 169–183.
- Datta, A., Nayak, D., Sinhababu, D., Adhya, T., 2009. Methane and nitrous oxide emissions from an integrated rainfed rice–fish farming system of Eastern India. *Agriculture, Ecosystems & Environment* 129, 1-3, 228–237.
- Datta, S., Singh, J., Singh, S., Singh, J., 2016. Earthworms, pesticides and sustainable agriculture: a review. *Environmental Science and Pollution Research* 23, 9, 8227–8243.
- De, K., Dwivedi, A.K., 2024. Bridging gaps in the Indian freshwater biodiversity conservation through science-based and policy-backed recommendations. *Ecology & Hydrobiology* 24, 1, 169–177.
- Debnath, D., Babu, S., Ghosh, P., Helmar, M., 2018. The impact of India's food security policy on domestic and international rice market. *Journal of Policy Modeling* 40, 2, 265–283.
- Declaration, R., 1996. Rome declaration on world food security and world food summit plan of action.
- Deepitha, R., Roy, S.D., Sankar, R.K., Saravanan, K., Haridas, H., Praveenraj, J., 2019. Rice fish culture for nutritional and livelihood security in coastal india. *An Overview of Integrated Farming Systems of Coastal India* p. 113.
- Dey, A., Sarma, K., Kumar, U., Mohanty, S., Kumar, T., Bhatt, B., 2019. Prospects of rice-fish farming system for low lying areas in bihar, india. *Organic Agriculture* 9, 99–106.
- Dey, M.M., Spielman, D.J., Haque, A.M., Rahman, M.S., Valmonte-Santos, R., 2013. Change and diversity in smallholder rice–fish systems: Recent evidence and policy lessons from Bangladesh. *Food Policy* 43, 108–117.
- Divakar, H., Mishra, R., Joshi, S., Kulkarni, B., Narayanan, P., Singh, R., Divakar, G.V., 2024. Need for advocacy around eating right: A call for reducing the burden of malnutrition—a pilot study. *The Journal of Obstetrics and Gynecology of India* pp. 1–7.
- Dorin, B., 2022. Theory, practice and challenges of agroecology in India. *International Journal of Agricultural Sustainability* 20, 2, 153–167.
- Duan, Y., Li, Q., Zhang, L., Huang, Z., Zhao, Z., Zhao, H., Du, J., Zhou, J., 2022. Toxic metals in rice-fish co-culture systems and human health. *Ecotoxicology and Environmental Safety* 241, 113797.
- Duncan, N., de Silva, S., Conallin, J., Freed, S., Akester, M., Baumgartner, L., McCartney, M., Dubois, M., Sellamuttu, S.S., 2021. Fish for whom?: Integrating the management of social complexities into technical investments for inclusive, multi-functional irrigation. *World Development Perspectives* 22, 100318.
- van Ewijk, E., Ros-Tonen, M.A., 2021. The fruits of knowledge co-creation in agriculture and food-related multi-stakeholder platforms in Sub-Saharan Africa—a systematic literature review. *Agricultural systems* 186, 102949.
- Fan, M., Hu, T., Zhao, S., Xiong, S., Xie, J., Huang, Q., 2017. Gel characteristics and microstructure of fish myofibrillar protein/cassava starch composites. *Food Chemistry* 218, 221–230.

- Feng, J., Li, F., Zhou, X., Xu, C., Fang, F., 2016. Nutrient removal ability and economical benefit of a rice-fish co-culture system in aquaculture pond. *Ecological Engineering* 94, 315–319.
- Feng, J., Liu, Y., Li, F., Zhou, X., Xu, C., Fang, F., 2021. Effect of phosphorus and potassium addition on greenhouse gas emissions and nutrient utilization of a rice-fish co-culture system. *Environmental Science and Pollution Research* 28, 38034–38042.
- Fiedler, J.L., Lividini, K., Drummond, E., Thilsted, S.H., 2016. Strengthening the contribution of aquaculture to food and nutrition security: The potential of a vitamin a-rich, small fish in bangladesh. *Aquaculture* 452, 291–303.
- Freed, S., Barman, B., Dubois, M., Flor, R.J., Funge-Smith, S., Gregory, R., Hadi, B.A., Halwart, M., Haque, M., Jagadish, S.K., et al., 2020a. Maintaining diversity of integrated rice and fish production confers adaptability of food systems to global change. *Frontiers in Sustainable Food Systems* 4, 576179.
- Freed, S., Kura, Y., Sean, V., Mith, S., Cohen, P., Kim, M., Thay, S., Chhy, S., 2020b. Rice field fisheries: Wild aquatic species diversity, food provision services and contribution to inland fisheries. *Fisheries Research* 229, 105615.
- Frei, M., Becker, K., 2005. A greenhouse experiment on growth and yield effects in integrated rice–fish culture. *Aquaculture* 244, 1–4, 119–128.
- Frei, M., Razzak, M., Hossain, M., Oehme, M., Dewan, S., Becker, K., 2007. Methane emissions and related physicochemical soil and water parameters in rice–fish systems in Bangladesh. *Agriculture, ecosystems & environment* 120, 2–4, 391–398.
- Fullbrook, D., 2013. Food security in the wider Mekong region. In *The water-food-energy nexus in the Mekong Region: Assessing development strategies considering cross-sectoral and transboundary impacts*. Springer, pp. 61–104.
- Garaway, C.J., Photitay, C., Roger, K., Khamsivilay, L., Halwart, M., 2013. Biodiversity and nutrition in rice-based ecosystems; the case of Lao pdr. *Human Ecology* 41, 547–562.
- Ge, L., Sun, Y., Li, Y., Wang, L., Guo, G., Song, L., Wang, C., Wu, G., Zang, X., Cai, X., et al., 2023. Ecosystem sustainability of rice and aquatic animal co-culture systems and a synthesis of its underlying mechanisms. *Science of The Total Environment* 880, 163314.
- Ghosh, S., Mistri, B., 2020. Drainage induced waterlogging problem and its impact on farming system: a study in Gosaba island, Sundarban, India. *Spatial Information Research* 28, 6, 709–721.
- Ghoshal, T., De, D., Biswas, G., Kumar, P., Vijayan, K., 2019. Brackishwater aquaculture: Opportunities and challenges for meeting livelihood demand in Indian Sundarbans. *The Sundarbans: A disaster-prone eco-region: Increasing livelihood security* pp. 321–349.
- Goda, A.M.S., Aboseif, A.M., Mohammedy, E.Y., Taha, M.K., Mansour, A.I., Ramadan, E.A., Abouhabana, N.M., Zaher, M.M., Otazua, N.I., Ashour, M., 2024. Earthen pond-based floating beds for rice-fish co-culture as a novel concept for climate adaptation, water efficiency improvement, nitrogen and phosphorus management. *Aquaculture* 579, 740215.
- Gogoi, B., Kachari, A., Das, D.N., 2015. Assessment of water quality in relation to fishery perspective in flood plain wetlands of Subansiri river basin Assam, India. *Journal of Fisheries and Aquatic Science* 10, 3, 171.
- Goswami, T., Ghosal, S., 2022. From rice fields to brackish water farms: changing livelihoods in agrarian coastal Bengal, India. *Asia-Pacific Journal of Regional Science* 6, 2, 453–484.
- Guo, H., Qi, M., Hu, Z., Liu, Q., 2020. Optimization of the rice-fish coculture in Qingtian, China: 1. effects of rice spacing on the growth of the paddy fish and the chemical composition of both rice and fish. *Aquaculture* 522, 735106.
- Guo, L., Zhao, L., Ye, J., Ji, Z., Tang, J.J., Bai, K., Zheng, S., Hu, L., Chen, X., 2022. Using aquatic animals as partners to increase yield and maintain soil nitrogen in the paddy ecosystems. *elife* 11, e73869.
- Halwart, M., 2008. Biodiversity, nutrition and livelihoods in aquatic rice-based ecosystems. *Biodiversity* 9, 1–2, 36–40.
- Halwart, M., Gupta, M.V., 2004. *Culture of fish in rice fields*. FAO; WorldFish Center.
- Haobijam, J., Marak, B.R., Rede, G., Mandal, T., 2016. Socio-economic characteristics of the farmers practicing paddy-cum-fish cultivation in the low lying paddy field of Manipur,

- Häsler, B., Dominguez-Salas, P., Fornace, K., Garza, M., Grace, D., Rushton, J., 2017. Where food safety meets nutrition outcomes in livestock and fish value chains: a conceptual approach. *Food security* 9, 1001–1017.
- Hebsale Mallappa, V.K., Pathak, T.B., 2023. Climate smart agriculture technologies adoption among small-scale farmers: a case study from Gujarat, India. *Frontiers in Sustainable Food Systems* 7, 1202485.
- Herlambang, A., Murwantoko, M., Istiqomah, I., 2021. Dynamic change in bacterial communities in the integrated rice–fish farming system in Sleman, Yogyakarta, Indonesia. *Aquaculture research* 52, 11, 5566–5578.
- Herrero, M., Thornton, P.K., Power, B., Bogard, J.R., Remans, R., Fritz, S., Gerber, J.S., Nelson, G., See, L., Waha, K., et al., 2017. Farming and the geography of nutrient production for human use: a transdisciplinary analysis. *The Lancet Planetary Health* 1, 1, e33–e42.
- Hou, Y., Jia, R., Sun, W., Li, B., Zhu, J., 2024. Influences of the integrated rice-crayfish farming system with different stocking densities on the paddy soil microbiomes. *International Journal of Molecular Sciences* 25, 7, 3786.
- Hu, Y., Yang, T., Liu, Y., Li, F., Xu, C., Fang, F., Feng, J., 2022. High fish stocking density weakens the effects of rice-fish co-culture on water eutrophication and greenhouse gas emissions. *Water, Air, & Soil Pollution* 233, 6, 222.
- Huang, J., Li, J., Zhou, W., Cheng, Y., Li, J., 2023. Effect of different rice transplanting patterns on microbial community in water, sediment, and *procambarus clarkii* intestine in rice-crayfish system. *Frontiers in Microbiology* 14, 1233815.
- Hussan, A., Chakrabarti, P., Sundaray, J., Das, A., Mohapatra, B., Ananth, P., 2018. Status and future of aquaculture development in Mizoram, India. *International Journal of Fisheries and Aquatic Studies* 6, 4, 42–48.
- Inayat, M., Abbas, F., Hafeez-ur Rehman, M., Mahmud, A., 2023. Optimizing rice-fish co-culture: Investigating the impact of rice spacing density on biochemical profiles and production of genetically modified tilapia (*Oreochromis* spp.) and *Cyprinus carpio*. *Plos one* 18, 12, e0295996.
- Islam, A.H.M.S., Barman, B.K., Murshed-e Jahan, K., 2015. Adoption and impact of integrated rice–fish farming system in Bangladesh. *Aquaculture* 447, 76–85.
- Jaacks, L.M., Bliznashka, L., Craig, P., Eddleston, M., Gathorne-Hardy, A., Kumar, R., Mohan, S., Norrie, J., Rajan, S., Roy, A., et al., 2023. Co-benefits of largescale organic farming on human health (bloom): Protocol for a cluster-randomised controlled evaluation of the Andhra Pradesh community-managed natural farming programme in india. *Plos one* 18, 3, e0281677.
- Jacobi, J., Mukhovi, S., Llanque, A., Augstburger, H., K`aser, F., Pozo, C., Peter, M.N., Delgado, J.M.F., Kiteme, B.P., Rist, S., et al., 2018. Operationalizing food system resilience: An indicator-based assessment in agroindustrial, smallholder farming, and agroecological contexts in Bolivia and kenya. *Land use policy* 79, 433–446.
- Jia, Y., Zheng, Y., He, T., Tang, H., 2023. Effects of integrated rice-frog farming on soil bacterial community composition. *Chilean journal of agricultural research* 83, 5, 525–538.
- Jiao, W., Cui, W., He, S., 2023. Can agricultural heritage systems keep clean production in the context of modernization? a case study of qingtian rice-fish culture system of China based on carbon footprint. *Sustainability Science* 18, 3, 1397–1414.
- Joffre, O.M., Freed, S., Bernhardt, J., Teoh, S.J., Sambath, S., Belton, B., 2021. Assessing the potential for sustainable aquaculture development in Cambodia. *Frontiers in Sustainable Food Systems* 5, 704320.
- Kathiresan, R., Vishnudevi, S., Jayakanth, U., 2020. Impact of agro-input use in integrated rice (*Oryza sativa* L.) farming system. *Indian Journal of Agronomy* 65, 2, 151–155.
- Kaushal, L.A., Prashar, A., 2021. Agricultural crop residue burning and its environmental impacts and potential causes–case of northwest India. *Journal of Environmental Planning and Management* 64, 3, 464–484.
- Kerr, R.B., Madsen, S., Stü`ber, M., Liebert, J., Enloe, S., Borghino, N., Parros, P., Mutyambai, D.M., Prudhon, M., Wezel, A., 2021. Can agroecology improve food security and nutrition? a review. *Global Food Security* 29, 100540.
- Khumairoh, U., Lantinga, E.A., Handriyadi, I., Schulte, R.P., Groot, J.C., 2021. Agro-ecological mechanisms for weed and pest suppression and nutrient recycling in high yielding complex rice systems. *Agriculture, Ecosystems & Environment* 313, 107385.

- Kumar, R., Monobrullah, M., Bhatt, B., Raizada, A., Sen, A., Samal, S., Kumar, M., 2023. Productivity, energy use efficiency, economics and co2 emission from integrated fish-duck farming in floodplain wetland ecosystems of eastern India. *Indian Journal of Fisheries* 70,3.
- Laborte, A.G., de Bie, K.C., Smaling, E.M., Moya, P.F., Boling, A.A., Van Ittersum, M.K., 2012. Rice yields and yield gaps in Southeast Asia: past trends and future outlook. *European Journal of Agronomy* 36, 1, 9–20.
- Lansing, J.S., Kremer, J.N., 2011. Rice, fish, and the planet. *Proceedings of the National Academy of Sciences* 108, 50, 19841–19842.
- Li, F., Gao, J., Xu, Y., Nie, Z., Fang, J., Zhou, Q., Xu, G., Shao, N., Xu, D., Xu, P., et al., 2021. Biodiversity and sustainability of the integrated rice-fish system in hani terraces, Yunnan province, China. *Aquaculture Reports* 20, 100763.
- Li, S., Li, W., Ding, K., Shi, X., Kalkhajeh, Y.K., Wei, Z., Zhang, Z., Ma, C., 2024. Co-culture of rice and aquatic animals enhances soil organic carbon: A meta-analysis. *Science of The Total Environment* 955, 176819.
- Liu, D., Tang, R., Xie, J., Tian, J., Shi, R., Zhang, K., 2020. Valuation of ecosystem services of rice–fish coculture systems in Ruyuan county, China. *Ecosystem Services* 41, 101054.
- Liu, P., Ravenscroft, N., Harder, M.K., Dai, X., 2016. The knowledge cultures of changing farming practices in a water town of the southern Yangtze valley, China. *Agriculture and Human Values* 33, 291–304.
- Liu, Q., Zhang, L., Yang, Y., Zou, J., Yang, Y., Ge, J., Yan, H., He, K., Yang, C., Tahir, R., et al., 2024. Ecological performance of an integrated ex-situ rice-fish co-culture system. *Aquaculture* 582, 740511.
- Liu, S., Jiao, W., Min, Q., Yin, J., 2017. The influences of production factors with profit on agricultural heritage systems: A case study of the rice-fish system. *Sustainability* 9, 10,1842.
- Liu, X., Mao, P., Li, L., Ma, J., 2019. Impact of biochar application on yield-scaled greenhouse gas intensity: a meta-analysis. *Science of the Total Environment* 656, 969–976.
- Lu, J., Li, X., 2006. Review of rice–fish–farming systems in China—one of the globally important ingenious agricultural heritage systems (giahs). *Aquaculture* 260, 1–4, 106–113.
- Lv, W., Yuan, Q., Lv, W., Zhou, W., 2020. Effects of introducing eels on the yields and availability of fertilizer nitrogen in an integrated rice–crayfish system. *Scientific Reports* 10, 1, 14818.
- Mandal, B.K., Islam, A., Sarkar, B., Rahman, A., 2021. Evaluating the spatio-temporal development of coastal aquaculture: An example from the coastal plains of west bengal, india. *Ocean & Coastal Management* 214, 105922.
- Mandal, M., Ghosh, D., Karmakar, M., Mandi, S., Modak, P., Ghosh, B., Mandal, D., 2024. Rural child health in India: the persistent nature of deprivation, undernutrition and the 2030 agenda. *Environment, Development and Sustainability* 26, 2, 4837–4860.
- Mariyono, J., 2024. Sustainable intensification practices of fish-rice co-culture in Java, Indonesia: technical, socio-economic and environmental features. *Journal of Agribusiness in Developing and Emerging Economies* 14, 5, 1015–1032.
- McGarraghy, S., Olafsdottir, G., Kazakov, R., Huber, E., Loveluck, W., Gudbrandsdottir, I.Y., Cechura, L., Esposito, G., Samoggia, A., Aubert, P.M., et al., 2022. Conceptual system dynamics and agent-based modelling simulation of interorganisational fairness in food value chains: Research agenda and case studies. *Agriculture* 12, 2, 280.
- Mirhaj, M., Boit, A., Razzak, M., Wahab, M., 2013. Yield performance comparison between cultures of rice cum prawn (*Macrobrachium rosenbergii*) and rice cum fish (*Cyprinus carpio*, *Oreochromis niloticus*) in north-eastern Bangladesh. *Aquaculture* 392, 26–33.
- Mo, A., Dang, Y., Wang, J., Liu, C., Yang, H., Zhai, Y., Wang, Y., Yuan, Y., 2022. Heavy metal residues, releases and food health risks between the two main crayfish culturing models: Rice-crayfish coculture system versus crayfish intensive culture system. *Environmental Pollution* 305, 119216.
- Modak, K., Guru, N., Mishra, G., Sharma, B., 2024. Role of traditional farming practices of northeast india in soil and water conservation and sustainable nutrient management. In *Sustainable Land Management in India*. Springer, pp. 167–178.
- Mohanty, R.K., 2010. Impact of phased harvesting on population structure, feed intake pattern and growth performance of *Macrobrachium rosenbergii* deman (giant freshwater prawn) in polyculture with carps in concurrent rice–fish culture. *Aquaculture International* 18, 523–537.

- Mohanty, R.K., Jena, S., Thakur, A., Patil, D., 2009. Impact of high-density stocking and selective harvesting on yield and water productivity of deepwater rice–fish systems. *Agricultural Water Management* 96, 12, 1844–1850.
- Morri, E., Santolini, R., 2021. Ecosystem services valuation for the sustainable land use management by nature-based solution (nbs) in the common agricultural policy actions: A case study on the foglia river basin (marche region, italy). *Land* 11, 1, 57.
- Mottet, A., Bicksler, A., Lucantoni, D., De Rosa, F., Scherf, B., Scopel, E., L'opez-Ridaura, S., Gemmil-Herren, B., Bezner Kerr, R., Sourisseau, J.M., et al., 2020. Assessing transitions to sustainable agricultural and food systems: a tool for agroecology performance evaluation (tape). *Frontiers in Sustainable Food Systems* 4, 579154.
- Mridha, M., Hossain, M., Azad Shah, A., Uddin, M., Nahiduzzaman, M., 2014. Effects of stocking density on production and economics of all-male tilapia (*oreochromis niloticus*) culture in a rain fed rice–fish ecosystem. *Journal of Applied Aquaculture* 26, 1, 60–70.
- Muhammad, B., Khan, S., 2021. Understanding the relationship between natural resources, renewable energy consumption, economic factors, globalization and co2 emissions in developed and developing countries. In *Natural resources forum*, Vol. 45, Wiley Online Library, pp. 138–156.
- Myeni, L., Mahleba, N., Mazibuko, S., Moeletsi, M.E., Ayisi, K., Tsubo, M., 2024. Accessibility and utilization of climate information services for decision-making in smallholder farming: Insights from Limpopo province, South Africa. *Environmental Development* 51, 101020.
- Myllimngap, W., 2021. Agrobiodiversity and natural resource management in traditional agricultural systems of northeast India. *Agrobiodiversity & Agroecology* 1, 1, 1–23.
- Myo, A., Ajayi, O., Huang, F., Cheng, Y., Li, J., 2024. Valuation of ecosystem service of rice–fish coculture in Maubin district, Myanmar. *Anthropocene Coasts* 7, 1, 20.
- Nasiri, A.R., Shahangian, S.A., Kerachian, R., Zobeidi, T., 2024. Exploring socio-psychological factors affecting farmers' intention to choose a low-water-demand cropping pattern for water resources conservation: Application of the health belief model. *Agricultural Water Management* 295, 108768.
- Nayak, P., Nayak, A., Panda, B., Lal, B., Gautam, P., Poonam, A., Shahid, M., Tripathi, R., Kumar, U., Mohapatra, S., et al., 2018. Ecological mechanism and diversity in rice based integrated farming system. *Ecological Indicators* 91, 359–375.
- Nayak, P.K., Nayak, A., Kumar, A., Kumar, U., Panda, B., Satapathy, B., Poonam, A., Mohapatra, S., Tripathi, R., Shahid, M., et al., 2020. Rice based integrated farming systems in eastern India: a viable technology for productivity and ecological security. *NRRI research bulletin* , 24, 44.
- Nayak, P.K., Nayak, A., Panda, B., Senapati, A., Panneerselvam, P., Kumar, A., Tripathi, R., Poonam, A., Shahid, M., Mohapatra, S., et al., 2024. Rice-based integrated farming system improves the soil quality, bacterial community structure and system productivity under sub-humid tropical condition. *Environmental Geochemistry and Health* 46, 2, 65.
- Nguyen, V.K., Dumaresq, D., Pittock, J., 2018. Impacts of rice intensification on rural households in the Mekong Delta: emerging relationships between agricultural production, wild food supply and food consumption. *Food Security* 10, 1615–1629.
- Ning, K., Ji, L., Zhang, L., Zhu, X., Wei, H., Han, M., Wang, Z., 2022. Is rice–crayfish co-culture a better aquaculture model: from the perspective of antibiotic resistome profiles. *Environmental Pollution* 292, 118450.
- Niyaki, S.A.N., Allahyari, M.S., 2011. Economic factors on adoption of integrated rice–fish farming: Case of Tavalesh region, Iran. *Journal of Food, Agriculture & Environment* 9, 1, 599–603.
- Norbu, C., Downs, T.J., Yeboah, E., Scholtens, L., Bapat, J., Oelbermann, M., Kowsar, S.A., Webbe, J.A., Govaerts, B., Verhulst, N., et al., 2008. Experts address the question: “How can sustainable land management contribute to mitigating climate change?”. In *Natural Resources Forum*, Vol. 32, p. 252–256.
- Oehme, M., Frei, M., Razzak, M.A., Dewan, S., Becker, K., 2007. Studies on nitrogen cycling under different nitrogen inputs in integrated rice–fish culture in Bangladesh. *Nutrient Cycling in Agroecosystems* 79, 181–191.
- Ogunbode, C.A., Doran, R., B'ohm, G., 2020. Exposure to the IPCC special report on 1.5 c global warming is linked to perceived threat and increased concern about climate change. *Climatic Change* 158, 361–375.
- Padiyar, A.P., Dubey, S.K., Bayan, B., Chadag, V.M., Belton, B., Jena, J., Murthy, L.N., Karthikeyan, M., Murthy, C.K., 2024. Fish consumption in India: Patterns and trends. www.cgiar.org
- Paramesh, V., Ravisankar, N., Behera, U., Arunachalam, V., Kumar, P., Solomon Rajkumar, R., Dhar Misra, S., Mohan Kumar, R., Prusty, A., Jacob, D., et al., 2022. Integrated farming system approaches to achieve food

and nutritional security for enhancing profitability, employment, and climate resilience in India. *Food and energy security* 11, 2, e321.

Paul, B., Murari, K.K., Patnaik, U., Bahinipati, C.S., Sasidharan, S., 2023. Sustainability transition for indian agriculture. *Scientific Reports* 13, 1, 7290.

Pfendtner-Heise, J., Ackerschott, A., Schwenck, C., Lang, D.J., Von Wehrden, H., 2024. Making mutual learning tangible: Mixed-method delphi as a tool for measuring the convergence of participants' reciprocal understanding in transdisciplinary processes. *Futures* 159, 103365.

Phong, L., Van Dam, A., Udo, H., Van Mensvoort, M., Tri, L., Steenstra, F., Van der Zijpp, A., 2010. An agro-ecological evaluation of aquaculture integration into farming systems of the Mekong Delta. *Agriculture, ecosystems & environment* 138, 3-4, 232–241.

Van der Ploeg, J.D., Barjolle, D., Bruil, J., Brunori, G., Madureira, L.M.C., Dessein, J., Drag, Z., Fink-Kessler, A., Gasselin, P., de Molina, M.G., et al., 2019. The economic potential of agroecology: Empirical evidence from Europe. *Journal of rural studies* 71, 46–61.

Poonam, A., Saha, S., Nayak, P., Sinhababu, D., Sahu, P., Satapathy, B., Shahid, M., Kumar, G., Jambhulkar, N., Nedunchezhiyan, M., et al., 2019. Rice-fish integrated farming systems for Eastern India. *NRRI Research Bulletin*, 17, 33.

Powell, J.R., Welsh, A., Hallin, S., 2015. Microbial functional diversity enhances predictive models linking environmental parameters to ecosystem properties. *Ecology* 96, 7, 1985–1993.

Prost, L., Martin, G., Ballot, R., Benoit, M., Bergez, J.E., Bockstaller, C., Cerf, M., Deytieux, V., Hossard, L., Jeuffroy, M.H., et al., 2023. Key research challenges to supporting farm transitions to agroecology in advanced economies. a review. *Agronomy for Sustainable Development* 43, 1, 11.

Rautaray, S., Dash, P., Sinhababu, D., et al., 2005. Increasing farm income through rice (*Oryza sativa*)-fish-based integrated farming system in rainfed lowlands of assam. *The Indian Journal of Agricultural Sciences* 75, 2.

Rautaray, S.K., 2021. Field design for enhancing water productivity in waterlogged areas with efficient water harvesting and farming system. *Agricultural research* 10, 2, 255–261.

Ray, A., Chakraborty, A., 2021. The edible biota in irrigated, deepwater, and rainfed rice fields of Asia: A neglected treasure for sustainable food system. *Environment, Development and Sustainability* 23, 12, 17163–17179.

Reganold, J.P., Wachter, J.M., 2016. Organic agriculture in the twenty-first century. *Nature plants* 2, 2, 1–8.

Ren, L., Liu, P., Xu, F., Gong, Y., Zhai, X., Zhou, M., Wang, J., Wang, Z., 2023. Rice–fish coculture system enhances paddy soil fertility, bacterial network stability and keystone taxa diversity. *Agriculture, Ecosystems & Environment* 348, 108399.

Ren, W., Hu, L., Guo, L., Zhang, J., Tang, L., Zhang, E., Zhang, J., Luo, S., Tang, J., Chen, X., 2018. Preservation of the genetic diversity of a local common carp in the agricultural heritage rice–fish system. *Proceedings of the National Academy of Sciences* 115, 3, E546–E554.

Saikia, S., Das, D., 2009. Feeding ecology of common carp (*Cyprinus carpio* L.) in a rice–fish culture system of the apatani plateau (arunachal pradesh, india). *Aquatic Ecology* 43, 559–568.

Saikia, S., DN, D., 2008. Periphyton diversity in rice fish integrated fields at a high altitude of Eastern Himalaya. *International Journal of Ecology and Environment Sciences* 34, 299–306.

Saikia, S.K., 2024. Aquatic resources and feed diversification: Reviewing three case studies from south east asia with a viewpoint of trophic intensification in rice fish culture. *Aquaculture and Fisheries* 9, 4, 501–510.

Saikia, S.K., Das, D.N., 2015. Sustainable aquaculture: agro-ecological role of periphyton in ricefish farming. *Reviews in Aquaculture* 7, 3, 172–186.

Samaddar, A., Kacha, D., Kaviraj, A., Freed, S., Padiyar, A.P., Das, S., Saha, S., 2025a. A novel strategy to optimize resources to boost production in rice-fish coculture at ziro valley, india. *Aquaculture Reports* 41, 102679.

Samaddar, A., Kacha, D., Kaviraj, A., Freed, S., Panemangalore, A.P., Saha, S., 2025b. Rice-fish coculture: Enhancing resource management and food security. *Aquaculture* 595, 741476.

Samaddar, A., Panemangalore, A.P., Maliappan, S., Borah, G., Sikka, A., Kumar, G., 2024. Integrated agroecological rice fish farming in Andhra Pradesh, India: A case study. www.cgiar.org

- Sathoria, P., Roy, B., 2022. Sustainable food production through integrated rice-fish farming in india: A brief review. *Renewable Agriculture and Food Systems* 37, 5, 527–535.
- Selvan, T., Panmei, L., Murasing, K.K., Guleria, V., Ramesh, K.R., Bhardwaj, D., Thakur, C., Kumar, D., Sharma, P., Digvijaysinh Umedsinh, R., et al., 2023. Circular economy in agriculture: Unleashing the potential of integrated organic farming for food security and sustainable development. *Frontiers in Sustainable Food Systems* 7, 1170380.
- Shankar, B., Halls, A., Barr, J., 2004. Rice versus fish revisited: on the integrated management of floodplain resources in Bangladesh. In *Natural Resources Forum*, Vol. 28, Wiley Online Library, pp. 91–101.
- Sibhatu, K.T., Qaim, M., 2018. Meta-analysis of the association between production diversity, diets, and nutrition in smallholder farm households. *Food Policy* 77, 1–18.
- de Silva, V., Swain, M., Broderick, C., McKay, D., 2016. Does high level youth sports participation increase the risk of femoroacetabular impingement? a review of the current literature. *Pediatric Rheumatology* 14, 1–7.
- Sinclair, F., Wezel, A., Mbow, C., Chomba, S., Robiglio, V., Harrison, R., 2019. The contribution of agroecological approaches to realizing climate-resilient agriculture. *GCA: Rotterdam, The Netherlands*.
- Sinhababu, D.P., Poonam, A., 2022. Development in rice-fish-livestock farming for higher production and income in coastal areas. In *Transforming Coastal Zone for Sustainable Food and Income Security: Proceedings of the International Symposium of ISCAR on Coastal Agriculture*, March 16–19, 2021, Springer, pp. 261–276.
- Skokanova, H., Netopil, P., Havlíček, M., Sarapatka, B., 2020. The role of traditional agricultural landscape structures in changes to green infrastructure connectivity. *Agriculture, Ecosystems & Environment* 302, 107071.
- de Sousa, A.M.B., Santos, R.R.S., Moraes, F.H.R., Gehring, C., 2012. Exploring the potential for sustainable weed control with integrated rice-fish culture for smallholder irrigated rice agriculture in the Maranhao lowlands of Amazonia. *Renewable Agriculture and Food Systems* 27, 2, 107–114.
- Stadlinger, N., Berg, H., Van den Brink, P.J., Tam, N.T., Gunnarsson, J.S., 2018. Comparison of predicted aquatic risks of pesticides used under different rice-farming strategies in the Mekong Delta, Vietnam. *Environmental Science and Pollution Research* 25, 13322–13334.
- Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A.B., De Courcelles, V.d.R., Singh, K., et al., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems & Environment* 164, 80–99.
- Stratton, A.E., Kuhl, L., Blesh, J., 2020. Ecological and nutritional functions of agroecosystems as indicators of smallholder resilience. *Frontiers in Sustainable Food Systems* 4, 543914.
- Sun, G., Sun, M., Du, L., Zhang, Z., Wang, Z., Zhang, G., Xu, H., Wang, H., et al., 2021. Ecological rice-cropping systems mitigate global warming—a meta-analysis. *Science of the total environment* 789, 147900.
- Sunny, A.R., Sazzad, S.A., Prodhon, S.H., Ashrafuzzaman, M., Datta, G.C., Sarker, A.K., Rahman, M., Mithun, M.H., 2021. Assessing impacts of covid-19 on aquatic food system and small-scale fisheries in Bangladesh. *Marine policy* 126, 104422.
- Swaminathan, M., Kesavan, P., 2012. Agricultural research in an era of climate change. *Agricultural Research* 1, 3–11.
- Syaukat, Y., Julistia, D.R., 2019. Analysis of income and factors determining the adoption of integrated rice-fish farming system in seyegan district, sleman regency, yogyakarta, Indonesia.,
- Tao, L., Chai, J., Liu, H., Huang, W., Zou, Y., Wu, M., Peng, B., Wang, Q., Tang, K., 2022. Characterization and dynamics of the gut microbiota in rice fishes at different developmental stages in rice-fish coculture systems. *Microorganisms* 10, 12, 2373.
- Thilsted, S.H., Thorne-Lyman, A., Webb, P., Bogard, J.R., Subasinghe, R., Phillips, M.J., Allison, E.H., 2016. Sustaining healthy diets: The role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. *Food Policy* 61, 126–131.
- Tilley, A., Freed, S., Cagua, E.F., Longobardi, L., Sean, V., Mith, S., Miratori, K., Kura, Y., 2024. Retention of fish biodiversity in a mixed-use agroecosystem in Cambodia. *Hydrobiologia* 851, 6, 1475–1488.
- Tripathi, S., Srivastava, P., Devi, R.S., Bhadouria, R., 2020. Influence of synthetic fertilizers and pesticides on soil health and soil microbiology. In *Agrochemicals detection, treatment and remediation*. Elsevier, pp. 25–54.
- Triste, L., Debruyne, L., Vandenabeele, J., Marchand, F., Lauwers, L., 2018. Communities of practice for knowledge co-creation on sustainable dairy farming: features for value creation for farmers. *Sustainability Science* 13, 1427–1442.

- Uddin, M.N., Kabir, K.H., Roy, D., Hasan, M.T., Sarker, M.A., Dunn, E.S., 2021. Understanding the constraints and its related factors in tilapia (*Oreochromis sp.*) fish culture at farm level: A case from Bangladesh. *Aquaculture* 530, 735927.
- Upadhyay, A., Singh, B., 2013. Indigenous fishing devices in use of capture fishing in Tripura. *Indian Journal of Traditional Knowledge* 12.
- Uwimana, A., Van Dam, A.A., Wali, U.G., Irvine, K., 2022. Fluxes and retention of sediment and nutrients in valley bottom fish and rice farms and wetlands: impacts on surface water. *Wetlands Ecology and Management* 30, 2, 273–293.
- Verma, V., Vishal, B., Kohli, A., Kumar, P.P., 2021. Systems-based rice improvement approaches for sustainable food and nutritional security. *Plant Cell Reports* pp. 1–16.
- Wan, N.F., Li, S.X., Li, T., Cavaliere, A., Weiner, J., Zheng, X.Q., Ji, X.Y., Zhang, J.Q., Zhang, H.L., Zhang, H., et al., 2019. Ecological intensification of rice production through rice-fish co-culture. *Journal of Cleaner Production* 234, 1002–1012.
- Wang, E., Gao, Z., 2017. Chinese consumer quality perception and preference of traditional sustainable rice produced by the integrated rice–fish system. *Sustainability* 9, 12, 2282.
- Wang, M., Li, F., Wu, J., Yang, T., Xu, C., Zhao, L., Liu, Y., Fang, F., Feng, J., 2024. Response of ch₄ and n₂o emissions to the feeding rates in a pond rice-fish co-culture system. *Environmental Science and Pollution Research* 31, 40, 53437–53446.
- Wei, X., Zhu, Z., Wei, L., Wu, J., Ge, T., 2019. Biogeochemical cycles of key elements in the paddy-rice rhizosphere: microbial mechanisms and coupling processes. *Rhizosphere* 10, 100145.
- Wezel, A., Bellon, S., Doré, T., Francis, C., Vallod, D., David, C., 2009. Agroecology as a science, a movement and a practice. a review. *Agronomy for sustainable development* 29, 503–515.
- Wezel, A., Casagrande, M., Celette, F., Vian, J.F., Ferrer, A., Peigné, J., 2014. Agroecological practices for sustainable agriculture. a review. *Agronomy for sustainable development* 34, 1, 1–20.
- Wezel, A., Herren, B.G., Kerr, R.B., Barrios, E., Gonçalves, A.L.R., Sinclair, F., 2020. Agroecological principles and elements and their implications for transitioning to sustainable food systems. a review. *Agronomy for Sustainable Development* 40, 1–13.
- Willer, H., Trávníček, J., Schlatter, B., 2024. The world of organic agriculture. statistics and emerging trends 2024.
- Xie, J., Hu, L., Tang, J., Wu, X., Li, N., Yuan, Y., Yang, H., Zhang, J., Luo, S., Chen, X., 2011. Ecological mechanisms underlying the sustainability of the agricultural heritage rice–fish coculture system. *Proceedings of the National Academy of Sciences* 108, 50, E1381–E1387.
- Xie, J., Wu, X., Tang, J., Zhang, J., Chen, X., 2010. Chemical fertilizer reduction and soil fertility maintenance in rice-fish coculture system. *Frontiers of Agriculture in China* 4, 422–429.
- Xu, Q., Dai, L., Gao, P., Dou, Z., 2022. The environmental, nutritional, and economic benefits of rice-aquaculture animal coculture in China. *Energy* 249, 123723.
- Yang, Z., Feng, Y., Zhang, S., Hu, Y., Tang, Y., Gu, H., Gu, Z., Xu, Y., Cai, Y., Zhang, H., 2022. Effects of rice-prawn (*Macrobrachium nipponense*) co-culture on the microbial community of soil. *Applied Microbiology and Biotechnology* 106, 21, 7361–7372.
- Yassi, A., Farid, M., Anshori, M.F., Muchtar, H., Syamsuddin, R., Adnan, A., 2023. The integrated minapadi (rice-fish) farming system: Compost and local liquid organic fertilizer based on multiple evaluation criteria. *Agronomy* 13, 4, 978.
- Yi, S., 2019. Contingent valuation of sustainable integrated agriculture–aquaculture products: The case of rice–fish farming systems in South Korea. *Agronomy* 9, 10, 601.
- Yifan, L., Tiaoyan, W., Shaodong, W., Xucan, K., Zhaoman, Z., Hongyan, L., Jiaolong, L., 2023. Developing integrated rice-animal farming based on climate and farmers choices. *Agricultural Systems* 204, 103554.
- Yuan, J., Liao, C., Zhang, T., Guo, C., Liu, J., 2022. Advances in ecology research on integrated rice field aquaculture in China. *Water* 14, 15, 2333.
- Zhang, W., Xu, M., Lu, J., Ren, T., Cong, R., Lu, Z., Li, X., 2023. Integrated rice-aquatic animals culture systems promote the sustainable development of agriculture by improving soil fertility and reducing greenhouse gas emissions. *Field Crops Research* 299, 108970.

Zhang, Y., Liu, Y.H., Tang, D.Y., Zhang, J., Zhang, X.Y., Xu, C.W., Yuan, Y.J., Dai, C.C., 2024. Enhancing biomass and ecological sustainability in rice–fish cocropping systems through the induction of functional microbiota with compound biogenic bait. *Soil Ecology Letters* 6, 4, 240252.

Zhao, Z., Chu, C., Zhou, D., Wang, Q., Wu, S., Zheng, X., Song, K., Lv, W., 2021. Soil bacterial community composition in rice–fish integrated farming systems with different planting years. *Scientific Reports* 11, 1, 10855.

Zheng, L., Rong, Y., Guo, J., Yan, Y., Zhang, Y., Zhao, Y., Li, X., Wang, R. and Zhang, J., 2025. Improving economic efficiency of traditional rice-fish symbiosis system for sustainable mountainous development: A case study of the world agricultural heritage in Qingtian, China. *Ecological Frontiers*.

Disclaimer

This publication has been prepared as an output of the CGIAR Multifunctional Landscape Science Program and has not been independently peer reviewed. Responsibility for editing, proofreading, and layout, opinions expressed, and any possible errors lies with the authors and not the institutions involved. The views and opinions expressed in this publication are those of the author (s) and are not necessarily representative of or endorsed by CGIAR.



Contact

Ayan Samaddar, Post Doctoral Fellow, WorldFish India Ayan.Samaddar@cgiar.org

Cover & Layout: Ayan Samaddar/WorldFish

CGIAR is a global research partnership for a food-secure future. CGIAR science is dedicated to transforming food, land, and water systems in climate crisis. Its research is carried out by 13 CGIAR Centers/Alliances in close collaboration with hundreds of partners, including national and regional research institutes, civil society organizations, academia, development organizations and the private sector. www.cgiar.org

We would like to thank all funders who support this research through their contributions to the CGIAR Trust Fund: www.cgiar.org/funders.

To learn more about this Initiative, please visit [this webpage](#).

To learn more about this and other Initiatives in the CGIAR Research Portfolio, please visit www.cgiar.org/cgiar-portfolio

© 2025 WorldFish. Some rights reserved.

This work is licensed under a Creative Commons Attribution-Noncommercial 4.0 International Licence (CC BYNC 4.0).

