Fish-Rice Based Agroforestry Systems in India: Opportunities, Ecosystem Services, Climate Resilience, Livelihood Enhancement, and Future Research Directions

Manish Maan

Abstract

Integrated rice–fish systems are among the oldest forms of multi-trophic agriculture in Asia, yet their extension into explicitly agroforestry-oriented configurations—in which trees and woody perennials are deliberately combined with rice and aquaculture—remains poorly consolidated, particularly for India. This review synthesises evidence on fish-based rice agroforestry systems (FRAS) in India, drawing comparative insights from South and Southeast Asia, to assess their productivity, ecosystem services, climate resilience, livelihood outcomes, and research frontiers. Two findings frame the synthesis. First, rice–fish integration is well documented globally, but India contributes only a small share of the peer-reviewed literature, and the tree or agroforestry component specifically is thinly studied and agronomically contested, because woody perennials can compete with rice for light, water, and nutrients. Second, India's traditional systems—Apatani (Arunachal Pradesh), Zabo (Nagaland), Pokkali and the below-sea-level Kuttanad system (Kerala), and the bheri systems of the Sundarbans (West Bengal)—demonstrate long-standing integration of rice, fish, water, and, in several cases, trees and livestock, and are associated with substantial income gains relative to rice monoculture. Documented benefits include improved soil organic carbon, nutrient recycling, dietary diversification through small indigenous fish species, and enhanced flood and drought buffering, although methane dynamics involve clear trade-offs. Major constraints are land fragmentation, high initial investment in dykes and fish refuges, weak market and tenure institutions, and a shortage of long-term experimental data. We argue that the strongest near-term contribution of this field lies in treating agroforestry integration as an explicit research and policy frontier, aligned with India's National Agroforestry Policy (2014) and emerging blue-economy initiatives. We propose a future research agenda emphasising long-term factorial trials, standardised ecosystem-service accounting, and gender-disaggregated livelihood assessment.

[1]Doon School of Modern Agriculture and Forestry, DBS Global University Dehradun
manishmaan@dgu.ac.in Orcid id - https://orcid.org/0000-0003-1271-6754

Keywords: rice–fish farming; agroforestry; integrated farming systems; ecosystem services; climate-smart agriculture; rural livelihoods; blue economy; India

Introduction

Integrated farming systems (IFS) combine crops, aquaculture, trees, and livestock on the same land unit so that the by-products of one enterprise become inputs for another, raising land and water productivity per unit area while diversifying risk. Within this family, the integration of rice and fish is the most widely recognised expression in monsoonal Asia, valued for using the flooded paddy environment to produce a high-quality protein alongside the staple cereal. The Food and Agriculture Organization recognises traditional rice–fish systems among its Globally Important Agricultural Heritage Systems (GIAHS), reflecting both their antiquity—such practices span more than two millennia in parts of Asia—and their continuing relevance to food and livelihood security (Lu & Li, 2006; Min et al., 2009; FAO, 2024).

The evolution of rice–fish farming has moved from incidental capture of wild fish in paddies toward deliberate stocking, engineered refuges and trenches, and, more recently, multi-component systems integrating horticulture, poultry, ducks, and trees. Agroforestry—the deliberate combination of woody perennials with crops or animals—has historically developed on a parallel track in India, but its integration into rice landscapes is comparatively recent and unevenly documented (Gill et al., 2009) .

For India, the case for such systems is compelling. Smallholders and marginal farmers dominate the agricultural landscape, rural diets are frequently deficient in animal-source micronutrients, and rainfed and flood-prone lowlands are exposed to growing climatic variability. The latent scope is large: of an estimated area suitable for rice–fish integration in the tens of millions of hectares, only a small fraction is currently under such management (Sathoria & Roy, 2022). Bridging that gap is relevant not only to productivity but also to the national agroforestry and blue-economy agendas.

Yet the evidence base is fragmented and geographically skewed. A recent systematic review and meta-analysis of rice-aquaculture systems indicated that the academic literature is predominantly driven by China and Bangladesh, with India providing only a marginal contribution. The findings also highlighted continuous shortcomings in long-term evaluations, the quantification of ecosystem services, and socioeconomic disaggregation (Fernandez-Zatrate et al., 2025).

This review responds to that gap. Its objectives are to (i) clarify concepts and classifications of FRAS; (ii) map the status and regional distribution of relevant systems in India; (iii) critically appraise their ecosystem services, economic and livelihood impacts, and climate resilience; (iv) identify constraints, emerging technologies, and research gaps; and (v) derive policy implications and a future research framework. Throughout, the review prioritises critical synthesis over descriptive cataloguing, and is explicit about where the agroforestry (tree) component is genuinely evidenced versus where it remains an aspiration awaiting research.

Methodology

This article is a structured critical review that synthesises peer-reviewed and institutional evidence on fish-based rice agroforestry systems (FRAS), with India as its primary focus and South and Southeast Asia as a comparative reference. A narrative-synthesis approach was adopted deliberately, because the available evidence is heterogeneous in design, scale, and reporting—ranging from multi-season field experiments and short station trials to descriptive accounts of traditional systems, institutional bulletins, and policy documents—and is therefore not amenable to formal quantitative meta-analysis. Following the typology of Grant and Booth (2009), the review combines the interpretive, critique-oriented character of a critical review with a structured and transparent search process, and it is conducted and reported in line with the guidance for using a literature review as a research methodology set out by Snyder (2019). The intention throughout was best-evidence synthesis rather than exhaustive enumeration, in keeping with the objectives outlined in the Introduction.

Relevant literature was identified through structured searches of Scopus, Web of Science, and Google Scholar, supplemented by targeted retrieval of grey literature—research bulletins and technical reports of the Indian Council of Agricultural Research (ICAR) institutes, the Globally Important Agricultural Heritage Systems (GIAHS) dossiers of the Food and Agriculture Organization, and policy instruments of the Government of India. Search strings combined terms for the production system ("rice–fish", "rice-cum-fish", "integrated rice–fish", "paddy fish", "rice–fish–prawn"), for the agroforestry dimension ("agroforestry", "trees on bunds", "multipurpose trees", "integrated farming system"), and for thematic qualifiers ("ecosystem services", "soil organic carbon", "greenhouse gas", "methane", "climate resilience", "livelihood", "nutrition"), each combined with "India" and with the names of recognised indigenous systems ("Apatani", "Zabo", "Pokkali", "Kuttanad", "bheri"). The reference lists of retrieved articles and earlier reviews were additionally hand-searched (backward snowballing) to capture sources not well indexed by the primary databases, a step that proved especially important for the Indian institutional and regional literature.

Searches were conducted up to 2025. Because the conceptual and traditional foundations of these systems predate modern indexing, no lower date limit was imposed, so that seminal works on agroforestry and integrated farming were retained alongside contemporary studies. To improve transparency, the identification, screening, and selection of records were guided by the reporting principles of the PRISMA 2020 statement (Page et al., 2021), although the review was not registered as a formal systematic review and did not attempt quantitative effect-size pooling. Records were screened first by title and abstract and then at full text against three inclusion criteria: a study was retained if it (i) addressed rice–fish integration, an integrated farming system incorporating fish, or the deliberate combination of woody perennials with rice and aquaculture; (ii) was set in India or in an agro-ecologically comparable South or Southeast Asian context; and (iii) reported productivity, ecosystem-service, economic, livelihood, climate-resilience, or policy outcomes. Sources were excluded where they concerned rice monoculture or aquaculture in isolation from rice, were unavailable in English, or lacked sufficient methodological detail to interpret their findings.

Evidence was organised thematically around the review objectives—concepts and classification, regional distribution within India, system components, ecosystem services, economic and livelihood impacts, climate-change adaptation, constraints, emerging technologies, research gaps, and policy. From each source, information was extracted on the system type and its location, the components integrated (rice, fish, trees, livestock, and water management), and the reported outcomes, together with an appraisal of the nature and strength of the underlying evidence. A central analytical principle, applied consistently in the sections that follow, was to separate claims that are robustly evidenced for India—most clearly the economic and livelihood gains from integration—from those that remain weakly evidenced or merely asserted, in particular the agronomic effects and carbon contribution of the woody (tree) component. Because the quantitative outcomes reported in the primary studies derive from differing agro-ecologies and experimental designs, they are presented descriptively and are not treated as directly comparable; tabular summaries (Tables 1–4) are used to consolidate representative systems, ecosystem services, livelihood outcomes, and research priorities.

Two limitations of this approach should be acknowledged at the outset. First, the global peer-reviewed literature on rice–aquaculture systems is geographically skewed towards China and Bangladesh, with India contributing only a small share (Fernandez-Zatrate et al., 2025); the Indian evidence drawn upon here is therefore correspondingly uneven, and is thinnest precisely for the agroforestry component that the review seeks to foreground. Second, narrative synthesis, while appropriate to the heterogeneity of the material, yields conclusions that are interpretive rather than statistically pooled. The findings presented below should accordingly be read as a critical appraisal of the present state of knowledge and as the basis for the future research agenda developed later in this review.

Conceptual Framework of Fish-Based Rice Agroforestry

Definitions and classifications

Fish-based rice agroforestry systems (FRAS) are integrated land-use systems in which rice cultivation and fish (or other aquatic animal) production are combined with the deliberate management of woody perennials on bunds, dykes, field margins, or adjacent landscape tiers, often together with livestock, ducks, horticultural crops, or other complementary enterprises to enhance productivity, resource-use efficiency, ecosystem services, and livelihood resilience (Nair, 1993; Halwart & Gupta, 2004; Young, 1989; Sathoria & Roy, 2022). Systems are usefully classified along three axes. The first is temporal: concurrent (simultaneous) systems grow rice and fish together in the same waterlogged field, whereas rotational or alternating systems sequence a rice crop with an aquaculture phase, as in the rice-then-prawn cycle of coastal Kerala. The second is structural: trench-and-dyke, deepwater, and tiered hill systems differ in how water and refuge are engineered. The third is the agroforestry dimension proper: the position, density, and function of the woody component, ranging from a few multipurpose trees on bunds to a full upper-tier forest reserve, as in the three-tier Zabo system of Nagaland. (Frei, M., & Becker, K. ,2005)

It is important to state plainly that the tree component is the least standardised and least studied element. Much of what is labelled rice–fish agroforestry in India is, in practice, rice–fish integration with incidental trees on bunds; genuinely designed tree–rice–fish trials are scarce. This is not a weakness of the systems but of the evidence, and it defines one of the central research frontiers identified later.

Ecological interactions and nutrient cycling

The functional logic of FRAS rests on complementary niches. Fish forage on weeds, insect larvae, and detritus, contributing to pest and weed regulation and reducing the need for agrochemicals; their movement aerates and bioturbates the surface soil; and their excreta recycle nitrogen and phosphorus back to the rice crop. Nitrogen-fixing aquatic ferns such as Azolla, and the manuring effect of integrated ducks or livestock, further close nutrient loops. Trees on bunds can stabilise embankments, provide shade and windbreak, supply fodder, fuelwood, and fruit, and, where nitrogen-fixing species are used, contribute to soil fertility. Continuous return of organic matter and fish excreta has been associated with increased soil organic carbon in integrated rice–fish fields of eastern India (ICAR–NRRI, 2019).

These interactions are not uniformly positive, and a credible framework must represent the trade-offs. Woody perennials compete with rice for light, water, and nutrients and can impede mechanisation, so tree selection, spacing, and orientation are decisive for net outcomes. Likewise, the same flooded, organic-rich conditions that support fish also favour methanogenesis, creating a tension between aquatic productivity and greenhouse-gas mitigation that is examined in Section 6.

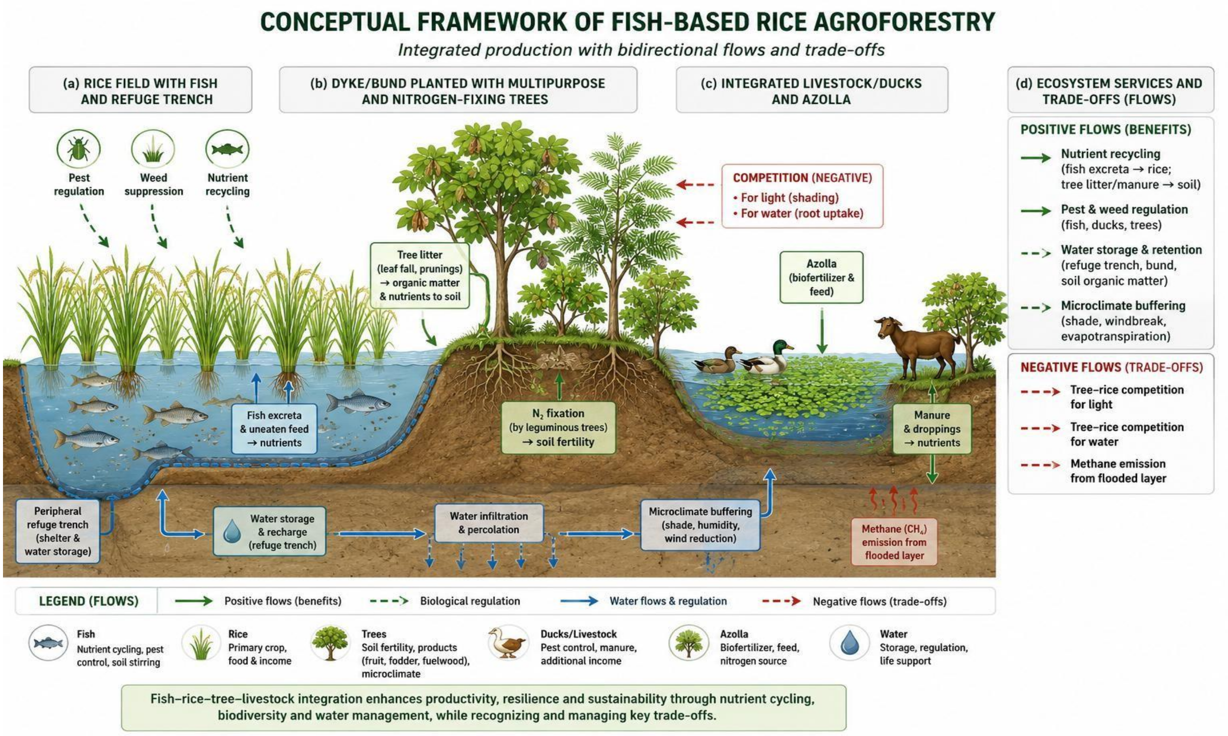


Figure 1. A schematic field cross-section.

Productivity pathways and resource-use efficiency

System productivity arises through three pathways: intensification (an additional aquatic yield from the same land and water), substitution (biological pest control and in-situ nutrient supply replacing purchased inputs), and diversification (a portfolio of outputs that stabilises income). Where these operate together, the land-equivalent ratio of integrated systems typically exceeds that of rice monoculture, even when the rice yield alone is similar or marginally lower. Resource-use efficiency is most evident for water in deepwater and rainfed lowland systems, where the same standing water serves both rice and fish, and for nutrients, where recycling reduces external dependence (Xie et al., 2011)

Status and Distribution in India

Despite a large latent area, adoption of rice–fish integration in India remains modest relative to potential (Sathoria & Roy, 2022), and dedicated tree-integrated variants are more limited still. Nonetheless, India hosts an exceptionally rich set of traditional integrated systems, several of which embody agroforestry principles and provide living templates for FRAS.

Eastern India

Eastern India—Odisha, West Bengal, Bihar, and parts of Jharkhand and Chhattisgarh—is the heartland of formal rice–fish research and extension. The ICAR–National Rice Research Institute (Cuttack) and ICAR–Central Institute of Freshwater Aquaculture (Bhubaneswar) have developed and disseminated rainfed lowland and deepwater models (ICAR–NRRI, 2019; Nayak et al., 2018). Field studies in rainfed medium and deepwater ecosystems of Odisha quantified species performance and water productivity under integration (Mohanty et al., 2004; Mohanty et al., 2009), and trials in the low-lying lands of Bihar demonstrated the prospects of rice–fish systems for waterlogged tracts (Dey et al., 2019).

Northeastern India

The Northeast offers the clearest indigenous agroforestry–aquaculture integration. The Apatani system of Ziro Valley, Arunachal Pradesh, integrates wet-rice terraces with fish and is associated with markedly higher net income than rice monoculture—on the order of two-thirds higher in early assessments (Saikia & Das, 2008). The Zabo system of Nagaland is explicitly three-tiered, reserving the upper hillslope as forest, the middle for settlement and water-harvesting ponds, and the lower for combined rice and fish, with grazing livestock linking the tiers—an archetype of fish-based rice agroforestry. Rainfed lowland rice–fish integration has also been shown to raise farm income in Assam (Rautaray et al., 2005).

Coastal and tribal systems

Coastal India sustains several brackish-water rice–fish/prawn systems known regionally as pokkali (Kerala), bheri (Sundarbans, West Bengal), gajani (Karnataka), and khazaan (Goa and Maharashtra). In the pokkali system, salt-tolerant rice is grown in the monsoon and followed by a prawn-farming phase, with crop residues feeding the shrimp and shrimp wastes fertilising the rice, under an essentially organic regime. The below-sea-level Kuttanad farming system of Kerala is itself recognised as a GIAHS. These systems are ecologically valuable but under pressure: the pokkali area is reported to have contracted substantially over recent decades, reflecting urbanisation, labour scarcity, and price disincentives (Jose et al., 2023).

Table 1. Representative traditional integrated rice–fish (and agroforestry) systems of India.

System	Region / State	Key integration features	Reported character / outcome
Apatani	Arunachal Pradesh	Wet-rice terraces with fish; bunds and surrounding vegetation	~65% higher net income vs. monoculture (Saikia & Das, 2008)
Zabo	Nagaland	Three-tier: forest (top), ponds + livestock (middle), rice + fish (bottom)	Explicit agroforestry–aquaculture template; rainwater-harvesting based (Singh et al., 2018; Amenla, 2021)
Pokkali / Kuttanad	Kerala	Rotational salt-tolerant rice then prawn; organic; below-sea-level (Kuttanad)	GI-tagged rice; Kuttanad is a GIAHS; area declining (Shamna & Nisha 2017; Jose et al. 2023; FAO 2013)
Bheri	Sundarbans, West Bengal	Sequential rice with prawn/fish in estuarine impoundments	Low-input kg/ha fish-prawn with rice (Halwart & Gupta 2004)
Rainfed lowland models	Odisha, Bihar, Assam	Trench-and-dyke and deepwater rice–fish; ICAR models	Higher water productivity and income (Mohanty et al., 2004, 2009; Dey et al., 2019)

Components of Fish-Based Rice Agroforestry Systems

Rice component

The rice crop anchors the system. System design favours varieties matched to water regime—medium and deepwater types for flood-prone tracts, and salt-tolerant landraces such as pokkali for coastal zones. Wider or modified spacing accommodates fish movement and can improve aquatic yield without proportionate loss of grain (ICAR–NRRI, 2019). Reduced agrochemical use, made possible by fish-mediated pest and weed control, also favours the retention of indigenous and organic-quality rices.

Fish component

Stocked species in Indian systems include Indian major carps (Catla catla, Labeo rohita, Cirrhinus mrigala), common carp (Cyprinus carpio), and the freshwater prawn (Macrobrachium rosenbergii), with brackish-water species in coastal rotations. Bottom-dwellers such as common carp and mrigal tolerate fluctuating dissolved oxygen well and perform robustly under integration (Mohanty et al., 2004). Small indigenous fish species—for example Amblypharyngodon mola—are increasingly valued for their micronutrient density and suitability to low-input fields, linking the fish component directly to nutritional outcomes.

Tree component

The woody component is the defining yet least-evidenced element of FRAS. Functions include embankment stabilisation, shade and windbreak, fodder, fuelwood, fruit, and—with nitrogen-fixing species—soil enrichment. The central agronomic caution is competition: trees and shrubs can depress rice yields through shading and water and nutrient uptake and can hinder mechanisation, so species choice (favouring deep-rooted, light-canopied, or nitrogen-fixing perennials), spacing, and bund placement are decisive (Rangappa et al. 2025).

Livestock integration

Ducks, poultry, and cattle are common fourth components. Ducks forage on pests and weeds and manure the water; poultry and dairy on pond dykes intensify nutrient cycling and diversify income. Integration of fish with poultry and ducks alongside dyke horticulture has produced large gains in production efficiency and employment in eastern India (Rautaray et al., 2005).

Wetland and biodiversity components

FRAS function as managed agro-wetlands. The standing water, refuges, and field margins support aquatic plants, invertebrates, amphibians, and birds, and the use of indigenous fish helps conserve agrobiodiversity. Although the ecological importance of India's biodiversity is frequently highlighted, it is not consistently quantified; therefore, establishing standard metrics (such as species richness and functional diversity) is necessary to validate these claims. (Nayak et al., 2018; Xie et al., 2011).

Ecosystem Services and Environmental Benefits

FRAS deliver provisioning, regulating, supporting, and cultural services. Provisioning is the most visible—grain, fish, fodder, fruit, and fuelwood from one unit of land. Supporting and regulating services, however, are where integration most clearly outperforms monoculture, and where measurement is weakest in the Indian literature.

Soil health and nutrient recycling improve as fish excreta and organic inputs raise soil organic carbon and biologically available nutrients, reducing reliance on synthetic fertiliser (ICAR–NRRI, 2019). Biodiversity conservation and pest and weed regulation arise from the trophic complexity of the system and the in-field role of fish and ducks as biological control agents. Water-use efficiency is enhanced where a single body of standing water serves both crop and aquaculture.

Greenhouse-gas dynamics deserve careful, non-promotional treatment. Flooded rice is a major source of methane, and the introduction of fish into rice fields can increase methane emission even as it raises soil organic carbon; an integrated rainfed rice–fish study in eastern India documented this trade-off in methane and nitrous oxide fluxes (Datta et al., 2009).

Table 2. Ecosystem services of FRAS, underlying mechanisms, and the state of Indian evidence.

Ecosystem service	Mechanism in FRAS	Evidence status (India)
Soil health / nutrient recycling	Fish excreta and organic inputs raise SOC and available N, P	Field evidence (ICAR–NRRI, 2019); needs standardisation
Pest & weed regulation	Fish and ducks consume larvae, weeds; reduced agrochemicals	Well attested qualitatively; few quantified India trials
Biodiversity conservation	Managed agro-wetland; indigenous fish; field-margin habitat	Asserted; rarely measured with standard indices
Water-use efficiency	Shared standing water for rice and fish	Demonstrated in deepwater/rainfed models (Mohanty et al., 2009)
GHG regulation	SOC gain vs. methanogenesis; tree C sequestration	Trade-offs documented (Datta et al., 2009); tree C unquantified
Provisioning (food, fuel, fodder)	Grain, fish, fruit, fuelwood, fodder from one unit	Strong; quantified in IFS demonstrations

Economic and Livelihood Impacts

The economic argument for integration is the strongest part of the Indian evidence base. By adding a fish (and often horticultural and livestock) income to rice, FRAS raise net returns, smooth seasonal cash flow, and generate year-round on-farm employment, which is particularly valuable for smallholders and for women, who often manage homestead aquaculture and dyke horticulture.

Quantitative illustrations from India are striking, though drawn from diverse designs and agro-ecologies and therefore not directly comparable. Apatani rice–fish farmers were estimated to earn about 65% higher net income than rice monoculture growers (Saikia & Das, 2008). Intensive fish-based integrated systems combining fish, poultry, and ducks with dyke vegetables and fruit at ICAR–Research Complex for Eastern Region, Patna reported very large gains in relative production efficiency and daily income, and roughly three-fold higher employment, relative to rice–wheat and sole-fish systems, alongside substantial in-situ nutrient contributions to the soil (ICAR–RCER, 2024). Location-specific integrated interventions in tribal clusters of Odisha have shifted households from subsistence toward market orientation, with sizeable per-hectare income increases (Kumar et al., 2024; Kumar et al., 2025).

Beyond income, FRAS contribute to nutritional security: the in-field harvest of small indigenous fish supplies animal protein and micronutrients to rural diets, complementing the cereal staple. Risk reduction is a further, often under-valued benefit—diversified outputs buffer households against the failure of any single enterprise, an advantage that compounds under climatic stress. Gender dimensions, by contrast, remain under-researched in India and warrant disaggregated study.

Table 3. Selected quantitative livelihood and productivity outcomes reported for integrated rice–fish/IFS systems in India.

System & location	Reported outcome	Source
Apatani rice–fish, Arunachal Pradesh	~65% higher net income vs. rice monoculture	Saikia & Das (2008)
Fish + poultry + duck + dyke horticulture, Bihar	Large gains in production efficiency; higher employment; higher daily income	ICAR–RCER, Patna (2024)
Deepwater rice–fish, Odisha	Improved yield and water productivity under high-density stocking	Mohanty et al. (2009)
Tribal integrated cluster, Odisha	Shift from subsistence to market orientation; income rise	ICAR field programme (c. 2023)
Rice–fish, low-lying Bihar	Demonstrated prospects for waterlogged tracts; added fish income	Dey et al. (2019)

Climate Change Adaptation and Resilience

FRAS are frequently presented as climate-smart, and the logic is sound where it is grounded in system design rather than slogan. Flood resilience is the clearest case: in flood-prone tracts of eastern and northeastern India, integrated systems convert excess water from a hazard into a productive resource for fish, while deepwater and salt-tolerant rices tolerate inundation and salinity. The pokkali rice of Kerala, prized for flood and salinity tolerance, has even been trialled in the cyclone-affected Sundarbans to cope with seawater incursion (Shaji, 2021). Drought and extreme-weather resilience derive from water storage in refuges and ponds, microclimate moderation by trees, and enterprise diversification that spreads risk. Comparative work on Indian smallholders in flood-prone and drought-affected districts underscores that adaptive capacity depends heavily on institutional support, information access, and social networks rather than on technology alone (Bhange et al., 2024). From a climate-smart-agriculture perspective, FRAS can in principle deliver the triple win of productivity, adaptation, and mitigation, but the mitigation leg is conditional on managing the methane trade-off and on realising—and measuring—the carbon benefits of the tree component.

Constraints and Challenges

Adoption is limited by interacting biophysical, economic, and institutional barriers. The most cited economic constraint is the initial investment required to build dykes, deepen refuges, and procure fingerlings—investment that small and marginal farmers, who dominate the target landscapes, find difficult, and which is amplified in flood-prone areas where stronger embankments are needed (Sathoria & Roy, 2022). Land fragmentation reduces the field sizes over which integration is efficient, and insecure or collective tenure (as in some coastal and estuarine systems) complicates long-term investment.

Institutional and market barriers include weak value chains and price realisation for both indigenous rice and fish, limited cold-chain and aggregation infrastructure, and thin extension support tailored to integrated rather than single-commodity farming. Knowledge gaps—especially on the tree component, on long-term ecosystem-service outcomes, and on gendered impacts—constrain both farmer decision-making and policy design. Technical limitations include the loss of wild small-fish populations to high-yielding monoculture and agrochemical use, the need for reliable fingerling supply, and the absence of standardised, locally validated designs for tree–rice–fish integration.

Emerging Technologies and Innovations

A new generation of digital tools could lower the management burden that limits FRAS adoption, though it must be stressed that most current evidence comes from aquaculture and rice systems broadly rather than from rice–fish agroforestry specifically. Precision aquaculture—smart sensors, automated feeders, machine vision, and cloud or edge analytics—enables real-time water-quality and fish-growth monitoring, and reviews from India describe how the Internet of Things, artificial intelligence, and big data are reshaping smart aquafarming through automation and predictive decision support (Huang 2025). Remote sensing and geographic information systems support site suitability assessment, water-quality and land-cover monitoring, and spatial planning of integrated systems, including for Indian waters.

For the agroforestry dimension specifically, opportunities include geospatial siting of tree–rice–fish layouts to optimise the shade–competition balance, drone-based crop and canopy monitoring, and decision-support tools that help farmers position bunds, refuges, and tree rows. Improved system designs—better trench-and-dyke geometry, selection of light-canopied and nitrogen-fixing trees, and integration with Azolla and duck components—represent low-technology innovation that is arguably more immediately deployable for smallholders than capital-intensive digital systems. The research challenge is to validate these tools under real, low-connectivity, smallholder field conditions rather than on research stations alone.

Research Gaps and Future Agenda

Five gaps stand out. First, and most fundamental, is the tree component: replicated, multi-location trials quantifying how species choice, density, and arrangement affect rice yield, fish yield, soil carbon, and microclimate are largely absent for India. Second is the shortage of long-term monitoring; most studies are short and station-based, leaving the durability of soil-carbon, biodiversity, and yield outcomes unproven. Third is inconsistent, non-standardised ecosystem-service accounting, which prevents meta-analysis and benefit transfer. Fourth is the thin socio-economic evidence, especially gender-disaggregated and value-chain analysis. Fifth is the near-absence of integrated greenhouse-gas budgets that net methane emission against soil and tree carbon sequestration under Indian conditions.

A future research framework should therefore prioritise: long-term factorial field experiments crossing tree, fish, and management treatments across agro-ecologies; a common protocol for measuring provisioning, regulating, and supporting services and full GHG budgets; participatory and gender-sensitive livelihood studies; and sustainability assessment frameworks (for example, multi-criteria or life-cycle approaches) that allow systems to be compared on productivity, profitability, sustainability, resilience, and ecosystem services simultaneously. Embedding such research in the network of ICAR institutes, agricultural universities, and agroforestry bodies would accelerate both evidence and uptake.

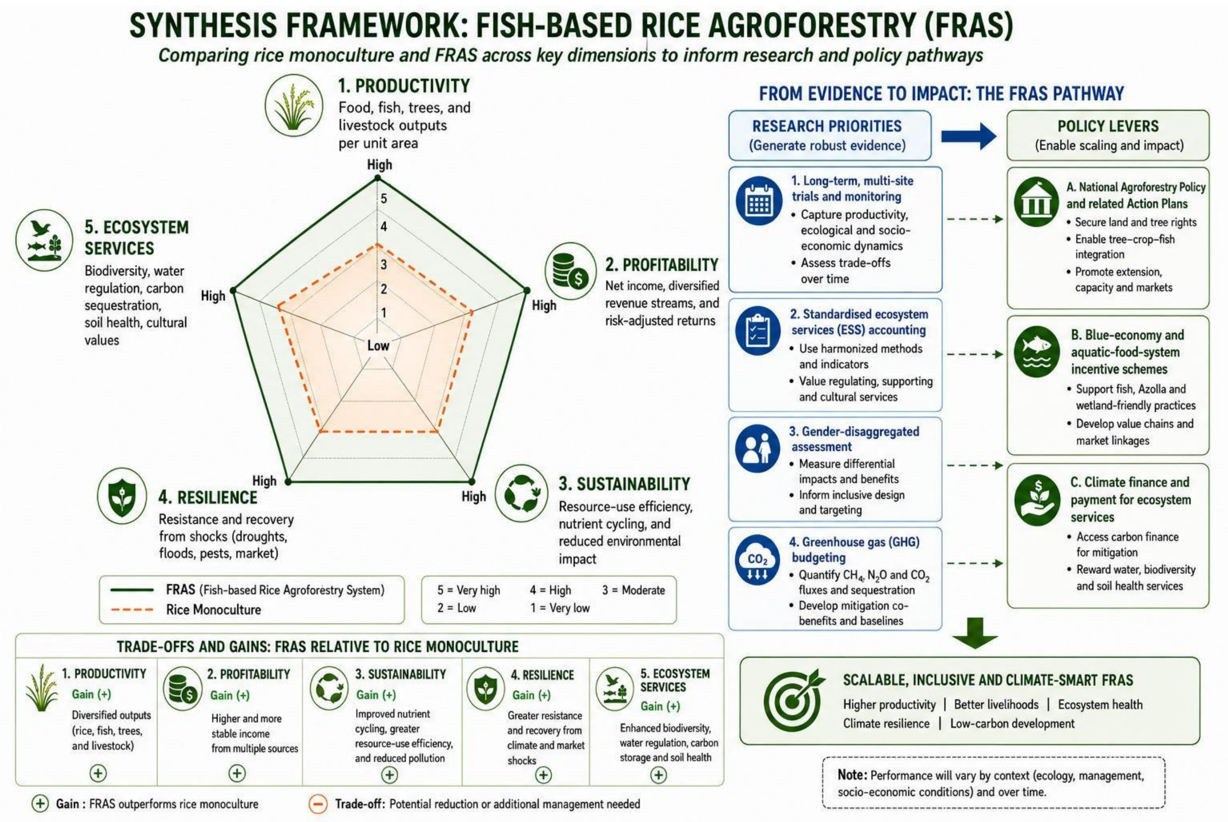


Figure 2. Synthesis framework.

Table 4. Priority research gaps and corresponding actions for FRAS in India.

Research gap	Priority action
Tree–rice–fish interactions unquantified	Multi-location factorial trials varying species, density, arrangement
Short, station-based studies	Establish long-term monitoring platforms across agro-ecologies
Non-standardised ecosystem-service metrics	Adopt common ESS and biodiversity measurement protocols
Thin socio-economic / gender evidence	Participatory, gender-disaggregated livelihood and value-chain studies
Incomplete GHG budgets	Net methane against soil + tree carbon under field conditions

Policy Implications for India

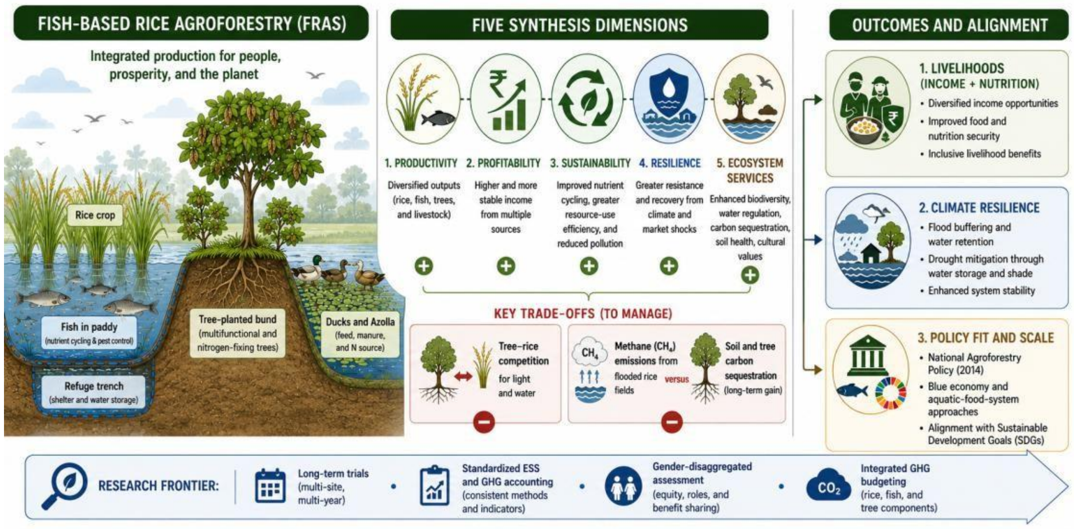
Policy alignment is unusually favourable. In 2014 India became the first country in the world to adopt a National Agroforestry Policy, explicitly to integrate trees, crops, and livestock and to resolve cross-sectoral bottlenecks among agriculture, forestry, water, and environment (Government of India, 2014). Subsequent instruments—the Sub-Mission on Agroforestry, the strengthening of the Central Agroforestry Research Institute, and relaxed tree-felling and transit rules in many states—have begun to address the regulatory disincentives to on-farm trees. FRAS sit squarely within this agenda and offer a concrete vehicle for delivering it in rice landscapes.

Three further policy streams reinforce the case. Blue-economy and fisheries-development initiatives provide a route to finance the aquaculture component and its market infrastructure. Climate-adaptation policy and India's nationally determined contributions create space for FRAS as a climate-smart practice, provided mitigation claims are evidence-based. And the systems map naturally onto several Sustainable Development Goals—notably no poverty (SDG 1), zero hunger (SDG 2), climate action (SDG-13), life below water (SDG-14), and life on land (SDG-15). The practical policy priorities are to converge these schemes at the level of the farm and landscape, to invest in extension tailored to integrated systems, to secure tenure in coastal and estuarine systems, and to fund the long-term research identified above so that incentives rest on robust evidence.

Conclusions

Fish-based rice agroforestry systems offer India a coherent pathway to raise land and water productivity, diversify smallholder incomes, improve rural nutrition, and build climate resilience, while drawing on a deep reservoir of indigenous integrated systems from the Apatani and Zabo highlands to the pokkali and bheri coasts. The evidence is strongest for economic and livelihood gains, solid but trade-off-laden for ecosystem services and climate resilience, and genuinely thin for the defining agroforestry (tree) component and for long-term, standardised, climate-accounted outcomes. The most valuable contribution this field can now make is to treat agroforestry integration not as an established practice to be promoted uncritically, but as a well-supported research and policy frontier—one that, with long-term factorial trials, standardised ecosystem-service and greenhouse-gas accounting, gender-sensitive livelihood research, and convergent policy under the National Agroforestry Policy and blue-economy agendas, could move from promising tradition to evidenced, scalable, climate-smart system.

Graphical Abstract



References

1. Amenla, I. (2021). *Zabo (Zabü) Farming of Kikruma Village, Nagaland, India*. In: Innovations in Agricultural Extension and Rural Development. Michigan State University Extension.
2. Bhange, P. B., Bonny, B. P., & Karat, S. (2024). Climate risk management among smallholder farmers: A comparative analysis of flood-prone Alappuzha and drought-affected Gondia in India. *Asian Journal of Agricultural Extension, Economics & Sociology, 42*(11), 148–161. https://doi.org/10.9734/ajaees/2024/v42i112600
3. Datta, A., Nayak, D. R., Sinhababu, D. P., & Adhya, T. K. (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.
4. Dey, A., Sarma, K., Kumar, U., Mohanty, S., Kumar, T., & Bhatt, B. P. (2019). Prospects of rice–fish farming system for low lying areas in Bihar, India. *Organic Agriculture*, 9(1), 99–106. https://doi.org/10.1007/s13165-017-0204-8
5. Fernandez-Zatrate, F., et al. (2025). *Sustainable rice–fish farming systems: A systematic review and meta-analysis*. *Aquaculture Research, 2025*, Article ID 4029275, 1–13. https://doi.org/10.1155/are/4029275
6. Food and Agriculture Organization (FAO). (2013). *Kuttanad Below Sea Level Farming System, India*. Globally Important Agricultural Heritage Systems (GIAHS), FAO, Rome.
7. Food and Agriculture Organization (FAO). (2024). *Rice–Fish Culture System, China*. Globally Important Agricultural Heritage Systems (GIAHS). Rome, Italy: FAO. Available at: FAO GIAHS Rice–Fish Culture System
8. Frei, M. and Becker, K. (2005), Integrated rice-fish culture: Coupled production saves resources. Natural Resources Forum, 29: 135-143.https://doi.org/10.1111/j.1477-8947.2005.00122.x
9. Gill, M. S., Singh, J. P., & Gangwar, K. S. (2009). Integrated farming system and agriculture sustainability. *Indian Journal of Agronomy*, 54(2), 128–139. https://doi.org/10.59797/ija.v54i2.4790
10. Government of India, Department of Agriculture & Cooperation, Ministry of Agriculture. (2014). *National Agroforestry Policy, 2014*. New Delhi: Government of India.
11. Grant, M. J., & Booth, A. (2009). A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal*, 26(2), 91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x
12. Halwart, M., & Gupta, M. V. (Eds.). (2004). *Culture of Fish in Rice Fields*. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO) and Penang, Malaysia: The WorldFish Center. 83 p. ISBN: 983-2346-33-9.
13. Huang, Y. P. (2025). Artificial Intelligence of Things (AIoT) advances in aquaculture: A review. *Processes, 13*(1), 73. https://doi.org/10.3390/pr13010073
14. ICAR–National Rice Research Institute. (2019). *Rice–fish integrated farming systems for Eastern India* (NRRI Research Bulletin No. 17; Poonam, A., Saha, S., Nayak, P. K., Sinhababu, D. P., et al.). Cuttack, Odisha: ICAR–NRRI.
15. Jose, A.E., Charitha, N., Karde, R., Bayskar, A., & Reddy, Y.A. (2023). *Pokkali Rice Cultivation: A Review on the Indigenous Rice Cultivation Method in Kerala*. International Journal of Environment and Climate Change, 13(8), 1090–1095. DOI: 10.9734/IJECC/2023/v13i82047.
16. Kumar, S., Shivani, Sarma, K., Dey, A., Kumar, R., Dubey, R., Raman, R. K., Kumar, S., & Das, A. (2024). Fish-based intensive integrated farming system for resource recycling, livelihood improvement and sustainable production in middle Indo-Gangetic Plains. *Indian Journal of Fisheries*, 71(4), 95–102. https://doi.org/10.21077/ijf.2024.71.4.115967-12

17. Kumar, S., Kumar, A., Shivani, Kumar, S., Kumar, R., Dubey, R., Shubha, K., Saurabh, K., Manibhushan, & Das, A. (2025). Enhancing farm productivity, profitability, sustainability and livelihood of small farm holders through integrated farming systems. *Indian Journal of Agricultural Sciences*, 95(3). https://doi.org/10.56093/ijas.v95i3.162923
18. Lu, J., & Li, X. (2006). Review of rice–fish farming systems in China: One of the Globally Important Agricultural Heritage Systems (GIAHS). *Aquaculture*, 260, 106–113.
19. Min, Q., Li, W., & Yang, G. (2009). Rice-fish culture in China. In Q. Min (Ed.), *Dynamic Conservation and Adaptive Management of China's GIAHS: Theories and Practices (I)* (pp. 37–88). Beijing, China: China Environmental Science Press.
20. Mohanty, R. K., Verma, H. N., & Brahmanand, P. S. (2004). Performance evaluation of rice–fish integration system in rainfed medium land ecosystem. *Aquaculture*, 230(1–4), 125–135. https://doi.org/10.1016/S0044-8486(03)00423-X
21. Mohanty, R. K., Jena, S. K., Thakur, A. K., & Patil, D. U. (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. https://doi.org/10.1016/j.agwat.2009.08.006
22. Nair, P. K. R. (1993). *An Introduction to Agroforestry*. Dordrecht, The Netherlands: Kluwer Academic Publishers, in cooperation with the International Centre for Research in Agroforestry (ICRAF).
23. Nayak, P. K., Nayak, A. K., Panda, B. B., Lal, B., Gautam, P., Poonam, A., Shahid, M., Tripathi, R., Kumar, U., Mohapatra, S. D., Jambhulkar, N. N., & Adhya, T. K. (2018). Ecological mechanism and diversity in rice-based integrated farming systems. *Ecological Indicators*, 91, 359–375. https://doi.org/10.1016/j.ecolind.2018.04.025
24. Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., et al. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*, 372, n71. https://doi.org/10.1136/bmj.n71
25. Rangappa, K., Singh, N. R., Joga, R. J., Mohapatra, K. P., Chandra, P., Choudhury, B. U., Moirangthem, P., Debnath, S., Chanu, L. J., Devi, N. P., et al. (2025). Tree crop interactions, productivity and physiological efficiency of understorey crops in *Alnus nepalensis* and *Gmelina arborea* based agroforestry systems in Eastern Himalayas. *Frontiers in Sustainable Food Systems*, 9, Article 1494371. https://doi.org/10.3389/fsufs.2025.1494371
26. Rautaray, S. K., Dash, P. C., & Sinhababu, D. P. (2005). Increasing farm income through rice (*Oryza sativa*)–fish based integrated farming system in rainfed lowlands of Assam. *Indian Journal of Agricultural Sciences*, 75(2), 79–82.
27. Saikia, S. K., & Das, D. N. (2008). Rice–fish culture and its potential in rural development: A lesson from Apatani farmers, Arunachal Pradesh, India. *Journal of Agriculture and Rural Development*, 6(1–2), 125–131. DOI: 10.3329/jard.v6i1.1667.
28. 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. https://doi.org/10.1017/S1742170522000126
29. Shaji, K. A. (2021, January 15). *Climate-adaptive and saline-water-resistant Pokkali rice could be the variety of the future*. Mongabay India.
30. Shamna, N., & Nisha, P. R. (2017). A study on farmers' perception on problems of Pokkali rice farming. *Indian Research Journal of Extension Education*, 17(4), 42–47.
31. Singh, R. K., Krujia, H., Bharali, R., & Borkotoky, D. (2018). *Zabo: A time-tested integrated farming system practiced by Chakhesang tribe of Nagaland*. Indian Farming, 68(3), 20–23.
32. Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, 104, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039
33. 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 of the United States of America (PNAS)*, 108(50), E1381–E1387. https://doi.org/10.1073/pnas.1111043108
34. Young, A. (1989). *Agroforestry for Soil Conservation*. Wallingford, UK: CAB International in association with the International Council for Research in Agroforestry (ICRAF).