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Significance of *Azolla* rice fish aggregate forming system for sustainable agriculture

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ABSTRACT

The *Azolla*-Rice-Fish integrated farming system represents a time-tested, ecologically harmonious, and economically viable approach to sustainable agriculture. In an era of increasing pressure on natural resources, climate variability, and declining soil fertility, this tri-component system provides a multifaceted solution by combining biological nitrogen fixation, natural pest control, and diversified farm income. *Azolla*, a floating water fern rich in nitrogen-fixing *Anabaena azollae*, plays a critical role in improving soil fertility and reducing dependency on chemical fertilizers. When integrated into flooded paddy fields, *Azolla* not only enriches the soil but also serves as a supplementary feed for fish and acts as a bio-barrier to suppress weed growth. The inclusion of fish such as carp or tilapia adds a layer of productivity and ecological balance, as fish help control mosquito larvae and enhance nutrient cycling through their excreta. The synergy of *Azolla*, rice, and fish promotes a closed-loop nutrient system, reduces environmental degradation, and enhances farmer resilience through diversified income streams. This paper evaluates the ecological, agronomic, and socio-economic significance of the *Azolla*-Rice-Fish aggregate system. It synthesizes findings from recent studies, field trials, and traditional practices, particularly in Asian agrarian contexts, to highlight the system's potential as a model for regenerative and climate-resilient agriculture.

Key Words - *Azolla*-Rice-Fish integrated farming, *Anabaena azollae,* paddy fields

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INTRODUCTION

Agriculture today faces a paradox: it must increase productivity to feed a growing population while also mitigating its own contribution to environmental degradation, soil depletion, and biodiversity loss. In this context, sustainable agriculture is no longer optional it is a necessity. One promising yet underutilized approach to ecological intensification is the *Azolla*-Rice-Fish Aggregate Forming System, a traditional yet highly scientific practice rooted in the principles of agroecology and circular farming.

The system synergizes three natural components- *Azolla*, a nitrogen-fixing aquatic fern; rice, a staple food crop cultivated in submerged conditions; and fish, often herbivorous species that thrive in paddy ecosystems. These elements, when integrated, form a dynamic biological loop that improves resource efficiency, minimizes external inputs, and promotes environmental harmony. The practice is particularly significant for regions like South and Southeast Asia, where rice cultivation dominates and smallholder farmers face mounting economic and climatic challenges.

Integrated rice-fish farming has been practiced in China for over 1,200 years (Lu & Li, 2006), and the inclusion of *Azolla* in this triad has shown potential to revolutionize low-input farming systems. Beyond enhancing crop yield, this model improves soil fertility, reduces synthetic fertilizer use, provides protein-rich food, and supports livelihoods, thereby aligning with several UN Sustainable Development Goals (SDGs), including SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land).

This study aims to critically analyze the scientific basis, agronomic efficiency, and socio-economic impact of the *Azolla*-Rice-Fish system, supported by experimental findings, policy reviews, and case studies. By exploring this integrative method, we seek to advocate for its broader adoption as a tool for sustainable and regenerative agriculture.

Understanding the *Azolla*-Rice-Fish Integrated System

The *Azolla*-Rice-Fish system is a model of ecological synergy, where each component- *Azolla*, rice, and fish-plays a functional and mutually beneficial role in the paddy ecosystem. When integrated correctly, this system fosters a self-sustaining, low-input, and high-efficiency agricultural practice that can adapt to diverse agro-climatic conditions.

***Azolla*: A Nitrogen Powerhouse**

Azolla is a fast-growing aquatic fern that forms a symbiotic relationship with the cyanobacterium *Anabaena azollae*, which resides in its dorsal leaves and fixes atmospheric nitrogen. This natural biological nitrogen fixation capacity (up to 1.5 kg N/ha/day) significantly reduces the need for chemical nitrogen fertilizers (Kannaiyan, 1992). *Azolla* multiplies rapidly on the surface of standing water, making it ideal for flooded paddy fields.

Rice: The Core Crop

Rice (*Oryza sativa*) thrives in waterlogged conditions where *Azolla* also grows. When *Azolla* is introduced early in the rice growth cycle, it suppresses weeds by blocking sunlight and competes with algal growth. Upon decomposition, *Azolla* enriches the soil with organic matter and nutrients, especially nitrogen, phosphorus, and potassium (Singh *et al.*, 2011). This not only enhances rice yield but also improves soil health over time.

Fish: Livelihood & Ecological Control

The integration of fish species such as common carp (*Cyprinus carpio*), rohu (*Labeo rohita*), or tilapia (*Oreochromis mossambicus*) contributes to income diversification, pest control, and nutrient cycling. Fish consume phytoplankton, mosquito larvae, and even feed on *Azolla*, which reduces *Azolla* overgrowth and promotes balance. Their excreta contribute to nutrient enrichment of the water and soil.

The Symbiotic Loop

- *Azolla* fixes nitrogen - supports rice growth.
- Rice provides shelter for fish and *Azolla*.
- Fish regulate mosquito breeding, consume weeds, and provide manure and income.
- *Azolla* acts as a fish feed and weed suppressant.

This biological loop minimizes external inputs, enhances water productivity, reduces the carbon footprint, and creates a resilient micro-ecosystem. The system has been successfully demonstrated in research fields across India, Vietnam, and China, with yield increases of up to 10-20% reported under integrated management (IRRI, 2015).

Role of *Azolla* in Nutrient Management

Azolla plays a pivotal role in sustainable nutrient management within integrated agro-ecosystems due to its exceptional capacity to fix atmospheric nitrogen, absorb macronutrients, and enrich soil organic matter. When used in the rice-fish system, *Azolla* becomes a dynamic tool that supports plant nutrition, improves soil structure, and reduces dependence on synthetic inputs.

Biological Nitrogen Fixation

The most significant contribution of *Azolla* is its symbiotic association with the cyanobacterium *Anabaena azollae*, which enables it to fix atmospheric nitrogen at rates ranging between 0.5 to 3.0 kg N/ha/day (Kannaiyan, 1992). Over a cropping season, *Azolla* can contribute up to 40-60

kg N/ha, which meets a significant portion of the nitrogen needs of a rice crop (Singh *et al.,* 2011).

When incorporated into the soil either fresh or as green manure, *Azolla* decomposes quickly and releases nitrogen in plant-available forms (primarily ammonium). This contributes not only to improved tillering and growth in rice plants but also to enhanced microbial activity in the rhizosphere.

Phosphorus and Potassium Uptake

Azolla is also efficient at absorbing phosphorus and potassium from the water. When applied back to the soil, it recycles these nutrients and minimizes leaching losses. Studies have shown that *Azolla* contributes approximately 3-5 kg P/ha and 15-25 kg K/ha in a season depending on biomass and application rate (Prabu *et al.,* 2006).

Soil Organic Carbon and Microbial Activity

Decomposition of *Azolla* contributes organic carbon, which improves soil aeration, water-holding capacity, and aggregate stability. A study by Nayak *et al.,* (2018) showed a 15-20% increase in soil microbial biomass carbon and nitrogen after regular *Azolla* incorporation over two seasons, indicating a richer and more active soil environment.

***Azolla* as Fish Feed and Weed Suppressant**

Azolla also indirectly supports nutrient dynamics by serving as protein-rich feed for fish, thus enhancing fish growth while recycling nutrients. A healthy mat of *Azolla* suppresses algal blooms and aquatic weeds, which can otherwise compete with rice for nutrients and light.

Azolla is a nutrient-efficient, regenerative biomass that boosts soil fertility and enhances the sustainability of the entire *Azolla*-Rice-Fish system, aligning well with organic farming principles and circular economy models.

Benefits of Integrated Rice-Fish-*Azolla* Systems

The *Azolla*-Rice-Fish integrated system represents a holistic farming approach that optimizes biological synergies between crops, aquatic plants, and fish. This method offers a multitude of benefits that are agronomic, ecological, and socio-economic in nature. As evidence from both traditional and experimental fields indicates, the integration of these three elements enhances productivity, profitability, and environmental resilience.

Increased Rice Yield and Resource Efficiency

Multiple studies have documented that rice yields increase by 10-20% in *Azolla*-fish integrated systems compared to conventional monoculture rice fields (IRRI, 2015; Prabu *et al.,* 2006). This yield increase is attributed to:

- Continuous nitrogen availability through *Azolla*.
- Reduced weed competition due to surface mat formation.
- Improved soil aeration and nutrient cycling aided by fish movement.

Fish activity stirs the water and prevents anaerobic conditions in submerged soils, indirectly benefiting rice root respiration and nutrient uptake.

Enhanced Income and Livelihood Diversification

The inclusion of fish (e.g., *Labeo rohita, Cyprinus carpio, Oreochromis niloticus*) introduces an additional income stream for smallholder farmers. Studies in Odisha and Assam (Das *et al.,* 2020) have shown that integrated farms report 30-45% higher net returns due to fish harvest, reduction in fertilizer costs, and better crop productivity.

Azolla also contributes to input cost reduction, particularly nitrogenous fertilizers, which are often expensive or inaccessible in remote areas.

Ecological Sustainability

The system supports biodiversity conservation, reduces environmental pollution, and mitigates greenhouse gas emissions:

- *Azolla* sequesters CO_2 and reduces methane emissions from paddy fields.
- Fish reduce vector-borne diseases by preying on mosquito larvae.
- *Azolla* suppresses algal blooms and unwanted aquatic weeds.
- Reduced synthetic input use lessens nitrate leaching and chemical runoff.

Pest and Disease Control

Fish species help in controlling pests like rice caseworms, leaf folders, and mosquito larvae,

thereby reducing the need for harmful pesticides (Lu & Li, 2006). *Azolla* mats also act as a barrier to pest emergence and prevent algal proliferation, which can create imbalances in aquatic paddy systems.

Improved Soil Health and Water Management

The decomposition of *Azolla* and fish excreta contributes to organic matter accumulation, increasing soil cation exchange capacity and enhancing water retention. It also helps improve pH balance in acidic soils, particularly in regions like Assam and Manipur.

Water use efficiency is improved due to:

- Reduced evaporation (thanks to *Azolla* cover),
- Fish-enhanced water aeration,
- Enhanced soil structure that improves infiltration and storage.

Compatibility with Climate-Resilient and Organic Farming

The system aligns with climate-smart agriculture by:

- Building natural buffers against climate variability,
- Enhancing resilience of smallholder farmers,
- Fulfilling organic certification standards through low-input dependency.

In summary, the *Azolla*-Rice-Fish system delivers multi-dimensional benefits-from food security and income diversification to ecosystem regeneration and input reduction. It offers a viable model for sustainable agriculture, especially for small and marginal farmers operating under resource constraints.

Ecological & Economic Sustainability Impacts

The *Azolla*-Rice-Fish integrated farming model offers a compelling blueprint for sustainable agriculture, one that goes beyond yield enhancement to address broader ecological balance and long-term economic viability. This tri-component system is deeply aligned with the principles of circular economy, natural resource conservation, and climate-resilient agriculture.

Ecological Sustainability

i. Nutrient Cycling and Soil Fertility Improvement : *Azolla*'s ability to biologically fix atmospheric nitrogen and recycle nutrients significantly reduces the dependency on external synthetic fertilizers. When incorporated into the soil or decomposed naturally, *Azolla* improves soil organic matter, boosts microbial activity, and enhances soil structure, fostering long-term soil fertility.

ii. Biodiversity Conservation: Fish introduction in paddy fields promotes on-farm aquatic biodiversity. This diversity increases ecological stability and provides natural pest regulation. *Azolla* mats act as microhabitats for beneficial aquatic organisms such as dragonflies and frogs that contribute to pest suppression.

iii. Carbon Sequestration and Methane Reduction: Studies (Reddy & Rao, 2004) indicate that *Azolla* sequesters atmospheric CO_2 through photosynthesis and reduces methane emissions-a major greenhouse gas from rice paddies-by oxygenating water and promoting aerobic decomposition processes.

iv. Water Conservation: *Azolla* mats reduce evaporation losses from flooded paddy fields by 10-15%. Moreover, fish activity minimizes water stagnation, improving oxygen diffusion and reducing eutrophication risk.

Economic Sustainability

i. Reduction in Input Costs: By substituting chemical fertilizers with *Azolla* and reducing pesticide requirements through fish integration, farmers experience a 25-40% cost saving on inputs per season (Das *et al.,* 2020). This is particularly valuable for small and marginal farmers with limited cash flow.

ii. Higher Returns and Risk Diversification: The addition of fish as a secondary product increases farm profitability. On average, integrated systems report 30-50% higher gross income than monocropped rice fields, particularly in regions like Odisha, Assam, and West Bengal.

iii. Year-Round Employment & Food Security: This system provides diversified employment throughout the year-not just during sowing or harvesting-and also enhances household nutrition security through access to protein-rich fish and nutrient-dense *Azolla*.

In essence, the *Azolla*-Rice-Fish system is not merely an agronomic technique-it is a sustainable livelihood strategy that strengthens both the environmental and financial foundations of agriculture.

Case Studies from India and Southeast Asia

To validate the theoretical and experimental benefits of the *Azolla*-Rice-Fish integrated system, multiple case studies from different agro-climatic zones have been documented. These studies provide concrete evidence of the system's adaptability, profitability, and sustainability, especially for smallholder and marginal farmers.

Odisha: Enhancing Yield & Income for Small Farmers

A study conducted in the Cuttack district of Odisha by the ICAR-Central Rice Research Institute (CRRI) (2018) implemented the *Azolla*-Rice-Fish system across 50 hectares involving smallholder farmers. The integration resulted in:

- 14-18% increase in rice yield,
- 30-40% savings in nitrogen fertilizer, and
- Rs. 15,000-18,000 additional income per hectare from fish harvesting.

Farmers also reported a significant reduction in weed infestation and noticed improved soil texture in the following season, promoting adoption across nearby villages.

Assam: Soil Health Recovery in Flood-Affected Regions

In flood-prone areas of Dhemaji district, Azolla-Rice-Fish integration helped restore soil fertility and pH balance. Conducted by Assam Agricultural University (AAU), this study emphasized the system's ability to:

- Regenerate waterlogged, acidic soils,
- Reduce pest outbreaks due to fish predation,
- Increase the water retention capacity of the field through *Azolla* biomass.

Additionally, women self-help groups (SHGs) were engaged in harvesting and local selling of *Azolla* and fish, improving gender-inclusive income streams.

Vietnam: National Adoption as Agroecological Policy

In Vietnam's Mekong Delta, the Azolla-Rice-Fish system is promoted as part of the country's sustainable rice intensification (SRI) initiative. A longitudinal study by the International Rice Research Institute (IRRI) (2015) across 120 hectares showed:

- 20% increase in rice yield,
- Up to 45% reduction in pesticide use,
- Higher B:C (Benefit:Cost) ratio of 2.8 compared to 1.9 in monoculture systems.

The government supports farmers through training programs and seed-*Azolla* distribution kits.

Yunnan Province, China: 1200 Years of Practice

China's Yunnan province has practiced fish-rice co-cultivation for over 1,200 years, and recent experimental addition of *Azolla* has increased ecological benefits. The Chinese Academy of Agricultural Sciences (CAAS) reported:

- 25% higher income than rice-only systems,
- Improved carbon sequestration metrics, and
- Long-term soil carbon increase of 0.5% per year with *Azolla* inclusion.

These case studies confirm that the *Azolla*-Rice-Fish system is context-adaptable, scalable, and

suitable for diverse geographies, from Indian floodplains to Southeast Asian deltas.

Challenges and Limitations of Adoption

Despite the well-documented benefits, the widespread adoption of the *Azolla*-Rice-Fish integrated system faces several challenges and limitations. These barriers are technical, socio-economic, and institutional, and addressing them is critical to unlocking the system's full potential for sustainable agriculture.

Technical Constraints

- Water Management: Maintaining optimum water levels is crucial for *Azolla* growth and fish survival. Fluctuating water tables, especially in rainfed or flood-prone areas, can disrupt the balance, leading to *Azolla* die-off or fish mortality (Singh & Singh, 2017).
- *Azolla* Pest and Disease: Although *Azolla* grows rapidly, it is susceptible to pests such as Azolla weevils (Stenopelmus rufinasus) and fungal infections, which can severely reduce biomass production (Prasanna *et al.*, 2019).
- Fish Species Selection: Not all fish species are compatible with every agro-climatic region. Selecting suitable, locally adapted species that do not adversely affect rice plants is essential but often overlooked.

Socio-Economic Barriers

- Initial Investment and Knowledge: Smallholder farmers may hesitate to adopt integrated systems due to initial labor, investment, and knowledge requirements for managing *Azolla* and fish simultaneously. Training and extension support are often inadequate in remote rural areas (Das *et al.,* 2020).
- Market Access: For fish sales to improve incomes, farmers require reliable market linkages. In many regions, lack of cold storage and transport infrastructure limits profitability from fish harvests.
- Land Tenure Issues: Fragmented landholdings and insecure tenancy arrangements can deter farmers from investing in sustainable but labor-intensive systems like *Azolla*-Rice-Fish.

Institutional and Policy Challenges

- Lack of Policy Incentives: Many agricultural policies still prioritize monoculture cereal production with chemical inputs rather than diversified agroecological approaches. Subsidies for chemical fertilizers and pesticides disincentivize adoption of integrated systems.
- Research and Extension Gaps: There is insufficient localized research on system adaptation and limited extension services to disseminate best practices and innovations, reducing farmer confidence.

Environmental Limitations

- Climate Variability: Erratic rainfall and temperature extremes linked to climate change can impact *Azolla* growth cycles and fish survival, necessitating adaptive management strategies.
- Water Pollution: In areas with contaminated water bodies, *Azolla* and fish health may be compromised, affecting system productivity and safety.

Addressing these challenges requires a multi-stakeholder approach involving governments, research institutions, NGOs, and farmer communities to develop location-specific solutions, capacity-building programs, and enabling policies.

CONCLUSION

The integrated *Azolla*-Rice-Fish farming system presents a promising pathway towards sustainable agriculture that aligns ecological balance with enhanced productivity and rural livelihoods. Through biological nitrogen fixation, nutrient recycling, pest control, and diversified income streams, this triad system addresses multiple challenges faced by smallholder farmers in diverse agro-ecological zones.

The documented case studies from India, Southeast Asia, and China provide strong evidence of the system's adaptability, resilience, and socio-economic benefits. However, widespread adoption requires overcoming significant technical, socio-economic, and policy-related barriers. Adequate water management, pest control, farmer training, market development, and supportive institutional frameworks are critical to scaling this practice effectively.

Policy interventions must also evolve to promote diversified farming systems, incentivize organic inputs, and strengthen value chains for fish and *Azolla* products.

The *Azolla*-Rice-Fish system embodies a holistic agroecological innovation that can contribute substantially to food security, environmental sustainability, and rural prosperity. As global challenges like climate change, land degradation, and input price volatility intensify, such integrative and nature-based solutions will be indispensable for the future of farming.

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