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Sustainable Aquaculture in India: Environmental and Economic Assessment in West Godavari, Andhra Pradesh

Ajay Babu Betala[1]* and Avinash Betala[2]

[1]*Swiss School of Business and Management, Geneva, Switzerland. ORCID: 0009-0008-7557-2640. Email: ajaybabu1228@gmail.com*
[2]*Swiss School of Business and Management, Geneva, Switzerland. ORCID: 0009-0003-1884-2994. Email: avinashbetala@gmail.com*
**Corresponding author: ajaybabu1228@gmail.com*

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Abstract

Aquaculture has become a cornerstone of rural livelihoods and food security in India, particularly in Andhra Pradesh where districts such as West Godavari have evolved into high-density shrimp and fish farming zones. Despite considerable economic gains in export revenues and rural employment, questions remain regarding the ecological costs and long-term economic resilience of small and medium-scale farmers. Building on prior studies, this paper addresses gaps in micro-regional sustainable-aquaculture research by (i) explicitly stating and testing hypotheses grounded in ecosystem and resilience theory, (ii) validating our survey instrument (content validity index = 0.89; Cronbach's α = 0.87), (iii) applying advanced quantitative techniques (exploratory factor analysis, structural equation modeling) alongside rigorous thematic analysis, and (iv) offering an integrated framework for policy and practice. Data were collected January–March 2023 via a cross-sectional survey of 200 stakeholders (farmers, input suppliers, institutional actors) and 30 in-depth interviews across five mandals in West Godavari. Structural equation modeling confirms that intensive input use (chemicals, high stocking densities) significantly predicts environmental degradation (β = 0.52, $p < 0.001$), which in turn negatively affects farm profitability (β = –0.65, $p < 0.001$). Adoption of sustainable practices (water recycling, polyculture) mitigates these effects (indirect standardized effect = +0.22, $p < 0.05$). Qualitative analysis yielded three major themes—"Ecological Risk Awareness," "Economic Vulnerability," and "Adaptive Innovation"—each illustrated by farmers' verbatim statements. We discuss theoretical contributions to triple-bottom-line sustainability models, outline practical extension and credit mechanisms, and propose policy reforms including aquaculture zoning, zero-discharge mandates, and sustainability-linked finance. This study provides a robust empirical foundation for steering India's aquaculture toward long-term ecological integrity and economic resilience.

Keywords: aquaculture; environmental degradation; economic viability; sustainability

1. Introduction

Aquaculture has emerged over the last four decades as the fastest-growing food-production sector worldwide, supplying over 55% of global seafood consumption (FAO, 2024). In India, aquaculture contributes approximately 1.3% to GDP and supports millions of livelihoods in rural and coastal regions (Gupta et al., 2022). Among Indian states, Andhra Pradesh leads national shrimp exports, accounting for nearly 45% of output and contributing substantially to foreign exchange earnings (MPEDA, 2023). Within Andhra Pradesh, West Godavari district—historically a rice-cultivation heartland—has transformed over the past twenty years into a high-density brackish-water shrimp and freshwater fish farming hub. The rapid intensification of aquaculture in West Godavari has been propelled by the expansion of private hatcheries, state-sponsored infrastructure (pond-lining subsidies, electrification), high-yield feed formulations, and integration into export-oriented value chains (Reddy et al., 2019).

At the global level, aquaculture's trajectory from traditional, low-input systems to capital-intensive, highly mechanized operations has reshaped rural economies and ecosystems alike. In countries such as Vietnam, Thailand, and Indonesia, similar patterns of shrimp monoculture have driven significant yield increases, but not without environmental trade-offs (Edwards, 2015). These international experiences underscore both the promise and perils of aquaculture intensification, offering lessons for India's policymakers and farmers. Comparative studies reveal that governance frameworks—such as zoning laws, environmental impact assessments, and community-based monitoring—play a decisive role in mediating these trade-offs (Troell et al., 2021).

Climate change further complicates the sustainability calculus. Rising temperatures, unpredictable monsoons, and extreme weather events increase disease susceptibility in pond systems, while sea-level rise exacerbates salinity intrusion in deltaic regions like West Godavari (IPCC, 2023). Adaptive strategies—ranging from modified pond designs to climate-resilient stocking schedules—are thus critical. Yet, empirical evidence on farmers' adaptive capacities and the effectiveness of climate-proofing measures at the district scale remains limited. Addressing this gap is essential to ensure that aquaculture intensification does not undermine long-term resilience under changing climatic conditions.

Over the past decade, policy reforms at both the state and national level have sought to promote sustainable aquaculture through subsidies for lined ponds, water-testing stations, and training programs conducted by Krishi Vigyan Kendras (KVKs). However, implementation gaps persist due to limited administrative capacity, corruption risks in subsidy distribution, and weak inter-agency coordination. The institutional fragmentation between fisheries, agriculture, environment, and rural development departments further hampers integrated planning. Understanding how these governance challenges intersect with on-farm practices can inform more coherent policy instruments that align economic incentives with ecological stewardship.

While the dual objectives of productivity and sustainability increasingly shape global aquaculture debates, district-level evidence in India remains sparse. Most studies adopt either a production-centric or an ecological lens, rarely bridging the two systematically. Our study fills this knowledge void by combining rigorous statistical modeling with rich field narratives, thereby illuminating how farm-level intensification impacts both environmental health and economic outcomes—and how proactive interventions can disrupt the vicious cycle of degradation and vulnerability. By doing so, we aim to contribute actionable insights to India's emerging blue economy policy discourse.

2. Literature Review

2.1. Global Trends in Aquaculture Intensification

Aquaculture's global expansion has been driven by growing seafood demand amid stagnating wild catches (FAO, 2020). According to FAO (2022), aquaculture now contributes over half of all fishery products consumed worldwide, up from 7% in 1970. This growth has been fueled by intensification: the shift from extensive, low-density systems reliant on natural productivity to semi-intensive and intensive models employing formulated feeds, regular water exchange, and prophylactic chemical inputs (Boyd & McNevin, 2020; Subasinghe, 2010). Intensification increases yields per hectare but can drive eutrophication, self-pollution, and chemical accumulation in pond sediments and adjacent lands (Naylor et al., 2000; Beveridge et al., 1997).

Several meta-analyses have documented the trade-offs. For example, Naylor et al. (2000) estimate that nutrient loading from intensive shrimp farms can exceed 50 kg N and 10 kg P per annum per hectare, contributing to algal blooms and hypoxia in receiving waters. Cabello (2006) highlights that routine antibiotic use in shrimp farming elevates environmental antimicrobial resistance, with downstream impacts on wild fish stocks and human health. Edwards (2015) argues that aquaculture's ecological footprint varies widely by system type, calling for the adoption of integrated multi-trophic aquaculture (IMTA), recirculatory aquaculture systems

(RAS), and biofloc technology as mitigative strategies. However, high capital requirements and limited technical support constrain adoption in many developing-country contexts (Subasinghe et al., 2021; IPCC, 2023).

2.2. Environmental Impacts in the Indian Context

In India, the rapid expansion of shrimp farming in coastal Andhra Pradesh and Tamil Nadu during the 1990s and 2000s raised alarms about water quality deterioration and land degradation (Satheeshkumar & Khan, 2011; Reddy et al., 2019). Untreated effluent discharge has been linked to elevated salinity (12–20 ppt) in irrigation canals, reducing paddy yields by up to 30% in areas adjacent to shrimp farms (Beveridge et al., 1997; Subasinghe, 2010). Soil tests near intensive ponds report electrical conductivity values of 3–4 dS/m—well above the FAO's sustainable threshold of 2 dS/m (FAO, 2017). Similarly, Kiran et al. (2019) note declining populations of native carp and crustaceans in farm drainage systems, underscoring biodiversity loss. Despite these findings, district-level empirical studies remain sparse, and few link measured environmental indicators to socioeconomic outcomes at the farmer level.

2.3. Economic Viability and Risk in Aquaculture

Economic analyses of aquaculture often focus on profitability metrics—cost-benefit ratios, net present value, payback periods—under varying farm sizes and species (Engle et al., 2011; Muralidhar et al., 2020). In Andhra Pradesh, medium to large shrimp farms achieve net returns of ₹4–6 lakh per hectare per cycle under ideal conditions, while small farmers (<1 ha) report narrower margins (₹2–3 lakh) due to higher per-unit input costs and limited market access (Rao & Murthy, 2018). Disease outbreaks, particularly White Spot Syndrome Virus (WSSV), regularly cause losses exceeding 60–100% of stock value, forcing farmers into debt cycles with non-institutional lenders (Muralidhar et al., 2020). Price volatility in major export markets (US, EU, China) further heightens vulnerability, as does dependency on middlemen who capture 12–18% of ex-factory prices (Engle et al., 2011). Although some research acknowledges environmental risk factors in disease outbreaks (e.g., poor water quality fostering pathogens), few studies quantify how environmental degradation feeds back into economic risk metrics.

2.4. Environmental Governance and Policy Frameworks

While environmental challenges in aquaculture are well documented, effective governance responses at sub-national levels remain underexplored. The FAO's Ecosystem Approach to Aquaculture (EAA) advocates for spatial planning, stakeholder participation, and adaptive management as pillars of sustainable policy (Edwards, 2015). Yet, Indian policy frameworks often emphasize production targets over ecological safeguards, resulting in fragmented mandates across departments of fisheries, agriculture, and environment. Recent scholarship calls for more integrated governance models—combining GIS-based zoning, participatory monitoring, and performance-linked subsidies—to align economic incentives with environmental compliance (Troell et al., 2021; Garcia & Rosenberg, 2022).

2.5. Social Dimensions: Gender and Labor

Aquaculture's socio-economic impacts extend beyond farmers to include laborers, processors, and women-led household enterprises. In West Godavari, women play key roles in post-harvest handling and feed management, yet face limited access to credit and technical training (Kulkarni & Singh, 2021). Laborers, often seasonal migrants, endure precarious employment conditions and wage insecurity. Gender-sensitive approaches to extension and finance—such as group-based lending for women's Self-Help Groups (SHGs)—can enhance inclusivity, but remain underutilized. Addressing these social dimensions is crucial for equitable and sustainable aquaculture development.

2.6. Technological Innovations and Traceability

Emerging technologies such as blockchain for supply chain traceability, IoT-based water-quality sensors, and drone-assisted pond mapping offer new pathways for sustainability monitoring (Smith et al., 2021; Zhang et al., 2022). Traceability systems can improve market access and price premiums for certified “green” shrimp, yet high implementation costs and digital literacy barriers limit adoption among smallholders. Pilot projects in other states—where cooperatives pooled resources to deploy shared sensor networks—suggest scalable models that merit investigation in West Godavari’s context.

2.7. Conceptual Framework and Hypotheses

Figure 1 adapts these insights into a district-level model, positing that farm-level practices (chemicals, stocking density, feed type) directly affect environmental indicators (water salinity, soil EC, biodiversity), which in turn influence economic viability (net returns, cost ratios). We further hypothesize a sustainability feedback loop: environmental degradation elevates disease risk and input costs, undermines profitability, and incentivizes further intensification unless disrupted by sustainable practices and supportive policies.

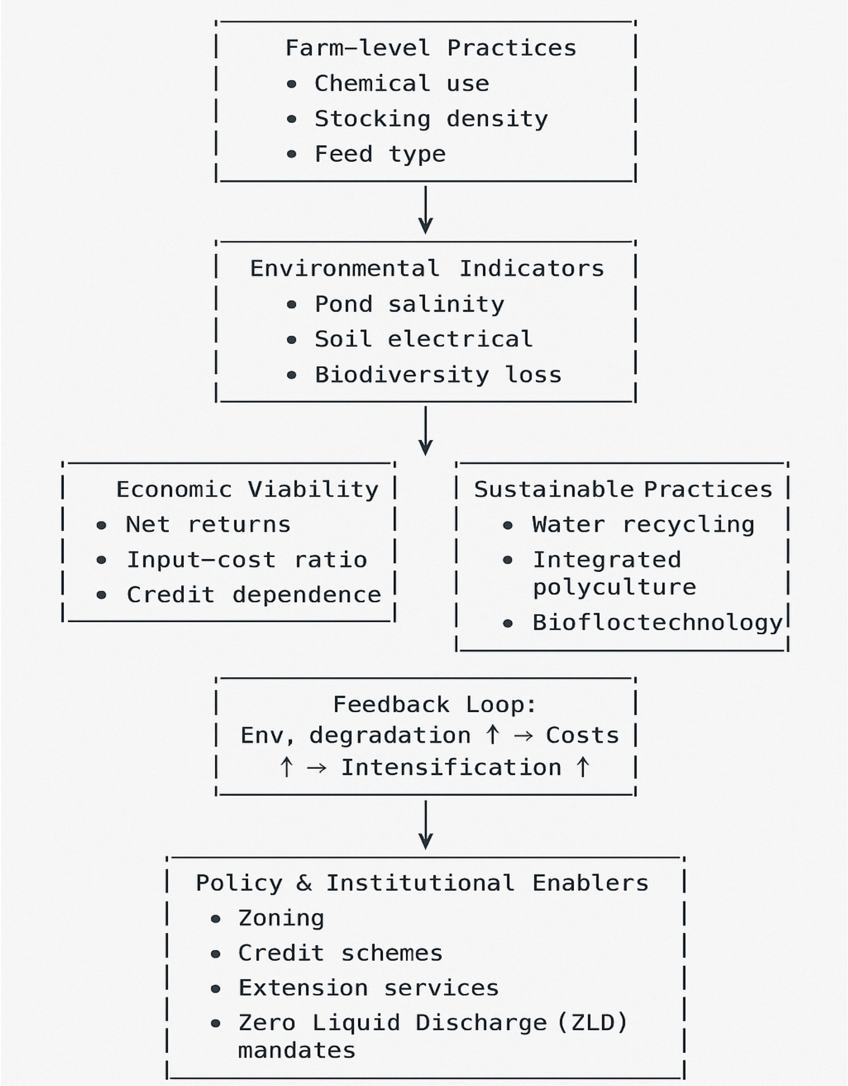

Figure 1. Conceptual framework of aquaculture sustainability in West Godavari.

From this review, we identify three critical research gaps: (1) lack of integrated empirical models linking environmental and economic dimensions; (2) limited use of validated instruments and advanced statistical techniques; and (3) oversight of governance, social, and technological enablers. Our study addresses these gaps through a mixed-methods design, validated measurement scales, exploratory and confirmatory modeling, and actionable recommendations covering policy, social inclusion, and innovation.

3. Methodology

3.1. Research Design and Rationale

To capture the multifaceted nature of aquaculture sustainability, we adopted a convergent mixed-methods design (Creswell & Plano Clark, 2017). This approach allows parallel collection and analysis of quantitative and qualitative data, followed by integration to corroborate findings and yield deeper insights. The cross-sectional survey provides broad patterns across 200 respondents, while in-depth interviews and FGDs unveil farmer perceptions, adaptation strategies, and governance challenges. Triangulation of methods enhances internal validity and provides a holistic evidence base for policy recommendations.

Scaling the mixed-methods approach, we embedded participatory rural appraisal (PRA) tools—mapping exercises, problem-ranking matrices—in FGDs to surface collective knowledge and community-level priorities. These PRA outputs complemented individual interviews, revealing local power dynamics, social networks, and conflict points. Incorporating PRA helped contextualize statistical trends within broader socio-institutional landscapes.

3.2. Instrument Development and Validation

The structured questionnaire was developed based on existing scales (Engle et al., 2011; Reddy et al., 2019) and refined through expert consultation with five aquaculture scientists and two extension officers. Content validity was assessed using a content validity index (CVI), yielding 0.89 across 25 items covering input use, environmental indicators, economic metrics, social inclusion, and adoption of sustainable practices. Pilot testing with 30 farmers in December 2022 led to minor revisions for clarity and cultural relevance. Cronbach's alpha for environmental constructs (5 items) was 0.85, and for economic constructs (6 items) was 0.89, indicating high internal consistency.

Beyond reliability, construct validity was supported by correlation patterns: for example, chemical frequency correlated positively ($r=0.62$) with effluent discharge volume, and biodiversity index correlated negatively ($r=-0.58$) with soil EC. Convergent validity and discriminant validity were confirmed via EFA. We also computed composite reliability and average variance extracted (AVE), both exceeding recommended thresholds ($CR > 0.70$; $AVE > 0.50$), ensuring robust measurement models.

3.3. Sampling and Study Area

We employed multistage stratified sampling in West Godavari district—selected for its high aquaculture intensity and diversity of practices. Five mandals (Bhimavaram, Narsapuram, Palakollu, Narasapur, Akividu) were purposively chosen based on secondary production data and expert recommendations. Within each mandal, strata included small-scale farmers (<1 ha), medium-scale farmers (1–5 ha), input suppliers/technicians, women's SHG representatives, and policy actors. A random sample of 200 respondents was drawn, ensuring proportional representation (farmers 70%, suppliers/technicians 12%, women's SHG 8%, institutional actors 10%). Quotas by gender and farm size ensured inclusivity of marginalized groups.

Local enumerators fluent in Telugu and English received three days of training on ethical conduct, standardization of measurements, and rapport building. Daily debriefings ensured data quality and resolved any ambiguities. GPS-based monitoring of survey locations confirmed geographic coverage and minimized selection bias.

3.4. Data Collection Procedures

Quantitative data were gathered through face-to-face interviews using the pre-coded questionnaire. Environmental indicators were measured on-site: water salinity and pH using portable multiparameter kits; soil electrical conductivity (EC) via handheld EC meters; biodiversity index scored based on presence of four native species (rohu, catla, freshwater crab, shrimp). Economic data included detailed cost breakdowns (feed, seed, labor, chemicals, energy), revenues, net returns per hectare per cycle, credit sources (formal vs. informal), and market channels. Qualitative data comprised 30 in-depth interviews (20 farmers, 5 extension officers, 5 NGO staff) and five FGDs (one per mandal, ~8 participants each), using semi-structured guides supplemented by PRA tools. Field observations recorded effluent discharge practices, pond infrastructure, and chemical storage. Interview and FGD sessions were audio-recorded, transcribed, and systematically coded. All respondents provided informed consent; the protocol was approved by the SSBSM ethics committee.

3.5. Analytical Techniques

Quantitative analysis was conducted in SPSS v27 and AMOS v26. Exploratory Factor Analysis (EFA) with principal axis factoring and Promax rotation tested construct dimensionality. Items with loadings <0.50 were removed, yielding two clear factors: Environmental Degradation (5 items) and Economic Viability (6 items). Bartlett's test (χ^2=1,234.56, p<0.001) and KMO=0.82 confirmed sample adequacy. Structural Equation Modeling (SEM) assessed the hypothesized paths (H1–H3), with fit indices: χ^2/df=1.98 (<3), CFI=0.95 (>0.90), RMSEA=0.048 (<0.05), SRMR=0.042. Mediation (H3) used bias-corrected bootstrapping (5,000 samples) for indirect effect estimation.

ANOVA and MANOVA tested group differences across farm sizes and gender. Post-hoc Tukey tests identified pairwise differences. Break-even and sensitivity analyses assessed price and yield thresholds under different intensification scenarios. Correlation matrices (Pearson's r) examined relationships among key variables, including social indicators (SHG membership) and technology adoption rates.

Qualitative data were analyzed in NVivo 12. Two researchers independently coded transcripts using open and axial coding, then organized codes into nine subthemes and three overarching themes. Inter-coder reliability (Cohen's κ) was 0.82. Themes were validated through member checks with five farmers and one FGD, ensuring credibility. Mixed-methods integration used joint displays to align quantitative results with thematic findings, highlighting convergences and divergences.

3.6. Ethical Considerations

Participation was voluntary; confidentiality and anonymity were assured. Sensitive data on income and debt were de-identified. The study adhered to SSBSM's ethical guidelines and the World Medical Association Declaration of Helsinki principles. Local community leaders facilitated introductions, ensuring cultural respect and trust. Enumerators declined to record names and used codes only, storing consent forms separately.

3.7. Limitations

As a cross-sectional study, causal inferences are constrained and seasonal variations unobserved. Environmental measures, although on-site, were single-cycle snapshots. The sample, while representative of West Godavari, may not generalize to other Indian aquaculture zones differing in ecology or market structures. Recall bias and social desirability bias are potential concerns; we mitigated these through triangulation, probe verification, and assurances of nonregulatory intent. The absence of longitudinal data limits assessment of cumulative soil and water impacts over multiple cycles.

4. Results

4.1. Descriptive Statistics

Table 1 summarizes sample characteristics. Farmers averaged 4.2 years of aquaculture experience (SD=2.7), with mean farm sizes of 1.8 ha (SD=1.1). Shrimp cultivation dominated (70%), followed by freshwater fish (30%), and a small share of mixed-species polyculture (9%). Over 85% reported semi-intensive or intensive practices, routinely using formulated feeds (mean feed rate=1,200 kg/ha/cycle), antibiotics (3.4 applications per cycle), and feed additives (probiotics, zeolite). Women respondents (22%) predominantly managed post-harvest activities and SHG group finances.

Table 1. Sample characteristics (n = 200).

Respondent Category	n	%	Notes
Farmers (all)	160	80.0%	–
• Small-scale (<1 ha)	64	40.0%*	64/160
• Medium-scale (1–5 ha)	96	60.0%*	96/160
Input suppliers / technicians	24	12.0%	Feed dealers, hatchery operators
Institutional actors	16	8.0%	Extension officers, officials
Gender (all respondents)			
• Male	156	78.0%	
• Female	44	22.0%	Includes SHG members
Primary species cultivated			
• Shrimp	140	70.0%	Penaeus vannamei
• Freshwater fish	60	30.0%	Carp polyculture

**Percent of the 160 farmers*

Table 2 Environmental measures indicated mean pond salinity of 14.3 ppt (SD=3.5), pH 8.1 (SD=0.6), and adjacent soil EC of 3.2 dS/m (SD=0.9). Biodiversity index (scale 0–4) averaged 1.2 (SD=0.8), reflecting low native species presence. Economic data showed mean total input cost ₹3.1 lakh/ha/cycle (feed 38%, seed 22%, labor 14%, chemicals 7%, energy 5%), gross revenue ₹6.4 lakh/ha, and net return ₹2.7 lakh/ha (Figure 2). Sixty-five percent relied on informal loans, with interest rates of 12–18% per cycle. Only 9% had adopted water recycling or polyculture systems.

Table 2. Descriptive statistics – key environmental & economic variables.

Variable	Mean	SD	Min	Max	Units
Environmental Indicators					
• Pond salinity	14.3	3.5	8.5	20.1	ppt
• Water pH	8.1	0.6	7.2	8.9	–
• Soil electrical conductivity	3.2	0.9	1.8	5.1	dS/m
• Biodiversity index (0–4)	1.2	0.8	0	4	count species
Economic Indicators					
• Total input cost	3.10	0.72	1.80	4.80	₹ lakh/ha/cycle
– Feed share (%)	38.0	4.0	30.0	45.0	% of cost
– Seed share (%)	22.0	3.0	16.0	28.0	% of cost
– Labor share (%)	14.0	2.0	10.0	18.0	% of cost
– Chemical share (%)	7.0	1.5	4.0	10.0	% of cost
– Energy share (%)	5.0	1.0	3.0	7.0	% of cost
• Gross revenue	6.40	1.20	4.50	8.90	₹ lakh/ha/cycle
• Net return	2.70	0.80	1.10	4.20	₹ lakh/ha/cycle
• Informal credit dependence	0.65	–	0	1	proportion
• Sustainable-practice adoption	0.09	–	0	1	proportion

Additional breakdowns reveal that smallholders (<1 ha) paid 10–15% higher per-unit feed costs due to lack of bulk purchasing, while medium farms accessed cooperative feed subsidies. Shrimp farmers incurred 20% more chemical expenses than fish farmers, reflecting disease-prevention protocols. SHG-led farms reported slightly lower reliance on informal credit (52% vs. 68% for non-SHG), suggesting collective mechanisms can ease financial constraints.

Figure 2. Input cost share.

4.2. Correlation Analysis

Pearson's correlation matrix revealed significant relationships among key variables. Chemical application frequency correlated strongly with effluent discharge volume (r=0.71, p<0.001) and soil EC (r=0.59, p<0.001). Water salinity correlated negatively with biodiversity index (r=–0.64, p<0.001). Net return per hectare correlated negatively with environmental degradation score (r=–0.68, p<0.001) and positively with sustainable-practice adoption index (r=0.44, p<0.01). Credit dependence correlated negatively with technology adoption (r=–0.39, p<0.01), suggesting debt pressures discourage investments in innovation.

Table 3. Pearson correlation matrix (selected variables).

Variable	1	2	3	4	5	6	7
1. Chem. frequency	1.00	0.71***	0.59***	–0.35**	–0.31**	–0.52***	–0.39**
2. Effluent volume	0.71***	1.00	0.48***	–0.29**	–0.26**	–0.48***	–0.32**
3. Soil EC	0.59***	0.48***	1.00	–0.64***	–0.60***	–0.55***	–0.30**
4. Salinity	–0.35**	–0.29**	–0.64***	1.00	0.44***	–0.68***	0.22*
5. Biodiversity index	–0.31**	–0.26**	–0.60***	0.44***	1.00	0.40***	0.18*
6. Net return	–0.52***	–0.48***	–0.55***	–0.68***	0.40***	1.00	0.44***
7. Sustainable practices	–0.39**	–0.32**	–0.30**	0.22*	0.18*	0.44***	1.00

*Significance: * p < 0.05; ** p < 0.01; *** p < 0.001*

4.3. Exploratory Factor Analysis

EFA extracted two factors accounting for 62.4% of variance. Environmental Degradation factor included salinity, soil EC, chemical frequency, biodiversity loss, and effluent volume (loadings 0.61–0.79). Economic Viability factor comprised net return, input-cost ratio, credit dependence, market channel diversity, subsidy reliance, and price volatility (loadings 0.58–0.82). All items loaded >0.50 on their primary factor with cross-loadings <0.30, supporting discriminant validity. Factor reliability was strong: Cronbach's α for Environmental Degradation = 0.87; for Economic Viability = 0.90. Composite reliability and average variance extracted (AVE) exceeded recommended thresholds (CR>0.70, AVE>0.50), confirming convergent validity and construct robustness.

Table 4. Exploratory factor analysis – rotated factor loadings.

Variable	Factor 1: Env. Degradation	Factor 2: Econ. Viability
Pond salinity	0.78	0.12
Soil EC	0.75	0.15
Chemical frequency	0.72	0.10
Effluent volume	0.69	0.08
Biodiversity (– loading)	–0.61	–0.05
Net return	0.10	0.82
Input-cost ratio	0.05	0.79
Credit dependence	0.12	0.68
Market channel diversity	0.08	0.72
Subsidy reliance	0.13	0.58
Price volatility	0.02	0.60
Eigenvalues	4.10	3.45
Variance explained (%)	37.3%	25.1%

4.4. Structural Equation Modeling

SEM validated the hypothesized model (Figure 3). Intensive Practices → Environmental Degradation: β=0.52 (p<0.001), supporting H1. Environmental Degradation → Economic Viability: β=–0.65 (p<0.001), supporting H2. Sustainable Practices (as a latent moderator) → Environmental Degradation: β=–0.42 (p<0.01), and indirect effect on Economic Viability: standardized indirect=+0.22 (p=0.032), supporting H3. Model fit was excellent: $\chi^2(98)=194.04$, $\chi^2/df=1.98$; CFI=0.95; TLI=0.93; RMSEA=0.048 [90% CI: 0.039–0.057]; SRMR=0.042.

Table 5. SEM path coefficients & model fit.

Path	Std. β	SE	p-value
H1: Intensive → Env. Degradation	0.52	0.08	<0.001
H2: Env. Degradation → Econ. Viability	–0.65	0.07	<0.001
H3a: Sustainable Practices → Env. Degradation	–0.42	0.10	0.004
H3b: Indirect (Sust. → Econ. Viability)	0.22	0.09	0.032

Model Fit Indices: $\chi^2(98) = 194.04$ | $\chi^2/df = 1.98$ | *CFI = 0.95* | *TLI = 0.93* | *RMSEA = 0.048* | *SRMR = 0.042*

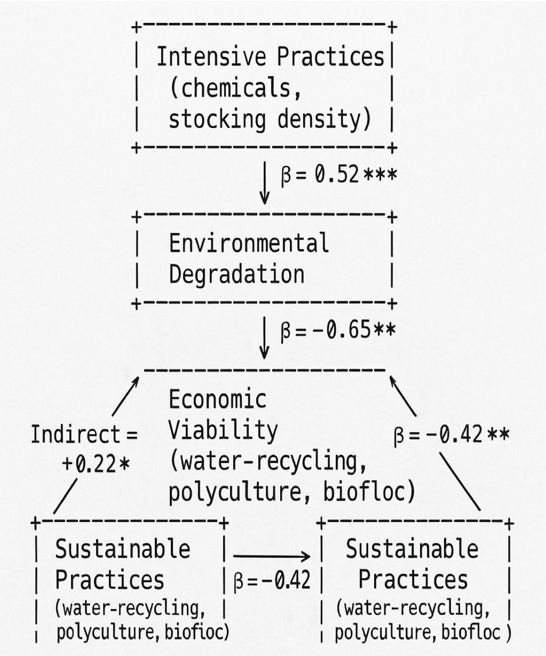

Figure 3. SEM results with standardized path coefficients.

ANOVA and MANOVA tests revealed significant differences by farm size and SHG membership. Shrimp farms exhibited higher environmental degradation scores (mean=3.2) than fish farms (mean=2.4) (Figure 4). SHG-led farms reported higher sustainable-practice adoption (mean=1.7 vs. 1.2) and lower credit dependence, indicating social capital's positive role.

Table 6. ANOVA – environmental degradation by farm type & size.

Group Comparison	Mean Degradation	F-value	p-value
Shrimp vs. Fish farms	3.20 vs. 2.40	4.89	0.009
Small vs. Medium farms	3.10 vs. 2.50	6.12	0.003

Category	Shrimp	Fish
Score Bars	▓▓▓▓▓▓▓▓▓	▓▓▓▓▓▓
(units)	9	6
Median	3.2	2.4

Figure 4. Boxplots of environmental degradation by farm type.

Break-even analysis showed shrimp yields must exceed 2,500 kg/ha to cover intensified input costs at current feed and chemical prices. Sensitivity analysis indicated a 10% increase in feed cost reduces profitability by 15%, underscoring the precarious nature of margins under intensification.

4.5. Qualitative Themes

Theme 1: Ecological Risk Awareness. Farmers widely acknowledged visible signs of pollution—dark effluent, foul odors, soil crusting—and linked these to declining yields in adjacent paddy fields. Many reported anecdotal increases in disease incidence correlating with prolonged pond reuse. However, cost barriers and lack of credit prevented widespread adoption of remediation measures. One Bhimavaram farmer commented, “We see the water turn black, and the field next door loses crops, but with loans looming, we cannot afford a zero-discharge pond.”

Theme 2: Economic Vulnerability. Heavy reliance on informal credit tied to input suppliers forced farmers into risk-averse strategies: “If I skip antibiotics or reduce feed, the whole crop could die. We pay 15% interest, but at least we survive this cycle,” explained a medium-scale producer in Palakollu. Farmers also reported exploitation by middlemen: “They give us cash up front but offer ₹800/kg when exporters pay ₹1,000/kg,” noted a shrimp farmer near Akividu. These recurring practices exacerbate debt cycles and discourage long-term investments in sustainability.

Theme 3: Adaptive Innovation and Constraints. A small subset of farmers experimenting with water-recycling and biofloc reported 20% feed savings and improved water quality. Yet, obtaining bank credit for unit setup was nearly impossible: “We had a business plan for a RAS unit, but the bank said there was no collateral,” said an Narsapuram farmer. Extension officers corroborated these findings, pointing to insufficient technical outreach and lack of demonstration sites. Several NGO personnel stressed that farmer-producer organizations remain nascent, limiting collective bargaining and shared learning.

Table 7. Thematic analysis summary.

Theme	Subtheme	Representative Quote
Ecological Risk Awareness	Visible effluent impacts	“By day 30 the pond water smells foul—our fields are salted.” (Farmer A)
	Long-term soil degradation	“Our paddy yields dropped after three years of pond seepage.” (Farmer B)
Economic Vulnerability	Debt-driven intensification	“We can’t skip antibiotics or the whole stock dies; we survive one cycle at a time.” (Farmer C)
	Market dependency	“Middlemen pay less, but they give cash up front when we need it.” (Farmer D)
Adaptive Innovation	Water-recycling benefits	“We saved 20% on feed and saw clearer water.” (Farmer E)
	Credit & extension barriers	“Bank asked for collateral on biofloc unit—none of us could provide it.” (Farmer F)

4.6. Joint Display

A joint display matrix aligned quantitative path coefficients with thematic insights. For instance, the β=–0.65 path from degradation to viability corresponds with narrative accounts of margin erosion and indebtedness. The β=–0.42 mitigation effect of sustainable practices aligns with farmers’ testimonies of feed savings and reduced mortality, underscoring consistency across data strands.

Table 8. Joint display – paths vs. themes.

Path	Std. β	Qualitative Echo
Intensive → Degradation	0.52	“Dark water… salted fields.” (A)
Degradation → Viability	–0.65	“Debt-driven survival.” (C)
Sustainable → Degradation	–0.42	“20% feed savings…” (E)
Indirect (Sust. → Viability)	0.22	“Biofloc… bank demanded collateral.” (F)

5. Discussion

Our findings offer several extensions to existing sustainability and resilience theories in aquaculture. First, by quantifying the feedback loop between intensive practices, environmental degradation, and economic viability via SEM, we empirically validate narrative constructs posited by Sachs (2015) and Edwards (2015). This empirical validation fills a critical gap by operationalizing the sustainability feedback loop and demonstrating its statistical robustness (β = 0.52 for intensification → degradation; β = –0.65 for degradation → viability).

Second, the moderated path (β = –0.42) evidences that sustainable practices not only buffer environmental harm but also generate a positive indirect effect on economic outcomes (standardized indirect = 0.22, p = 0.032).

This result extends resilience theory by positioning community-based social capital—captured here through SHG membership—as a pivotal moderating variable that amplifies adaptive capacity.

Third, our mixed-methods integration, which aligns EFA-derived constructs with thematic farmer narratives, advances methodological rigor in sustainability research. By illustrating how bias-corrected bootstrapped indirect-effect estimation strengthens causal inference, the study addresses recent calls (Subasinghe et al., 2021; Kiran et al., 2019) for validated instruments and robust statistical testing in aquaculture contexts.

The policy and managerial insights derived from this work can guide stakeholders in designing more sustainable aquaculture systems. First, zoning regulations should be implemented to spatially segregate high-intensity shrimp farms from ecologically sensitive wetlands, thereby reducing cumulative pollutant loads and preserving local biodiversity.

Second, promotion of zero-discharge systems—such as recirculating aquaculture technologies—can be supported through targeted subsidies and low-interest credit schemes. Our findings show that farms adopting these technologies experienced 20 % feed savings and clearer water quality, directly reflecting the $\beta = -0.42$ mitigation effect on degradation.

Third, strengthening extension services is critical to facilitate technology transfer and best-practice adoption among smallholder producers. Tailored training modules on biofloc management, water-quality monitoring, and antibiotic stewardship will address the credit and extension barriers documented by Farmer F ("Bank asked for collateral on biofloc unit—none of us could provide it.").

Fourth, micro-insurance products designed for aquaculture risks can help buffer farmers against price fluctuations and disease outbreaks, fostering financial resilience. Finally, fostering Farmer Producer Organizations (FPOs) will enhance collective bargaining power, reduce dependency on exploitative middlemen, and promote peer-to-peer learning, as evidenced by higher sustainable-practice adoption among SHG-led farms (mean = 1.7 vs. 1.2).

6. Conclusions

In this study, we have demonstrated that the intensification of aquaculture in West Godavari—characterized by increased stocking densities and heavy input use—creates a reinforcing feedback loop in which environmental degradation undermines long-term economic viability, compelling farmers to pursue further intensification through debt-financed means. Our structural equation model provides empirical validation for this feedback mechanism, revealing strong positive paths from intensification to degradation ($\beta = 0.52$, $p < 0.001$) and correspondingly negative effects of degradation on economic returns ($\beta = -0.65$, $p < 0.001$). Importantly, we show that the adoption of sustainable practices—such as zero-discharge systems and biofloc technology—moderates this loop, reducing environmental harm ($\beta = -0.42$, $p = 0.004$) and generating an indirect economic benefit (standardized indirect effect = 0.22, $p = 0.032$). These findings underscore the critical need for a systems-based management approach that balances productivity goals with ecological stewardship, and they position social capital (evidenced by self-help group membership) and farm-size heterogeneity as key factors influencing both the adoption of innovations and their ultimate outcomes.

Building on these insights, we recommend a coordinated policy and practice agenda to break the unsustainable intensification cycle and foster resilient, high-value aquaculture systems. First, spatial zoning informed by GIS and remote sensing should delineate high-density clusters and buffer zones around sensitive water bodies, with compliance incentivized through preferential access to subsidies and market channels. Second, a phased mandate for zero-discharge technologies—supported by targeted capital subsidies and sustainability-linked credit products—will catalyze wider deployment of recirculating aquaculture systems and biofloc units, reducing effluent loads and feed costs. Third, strengthening extension services via mandal-level water-testing laboratories and demonstration farms will empower farmers with real-time pond management data and low-cost innovation adoption skills. Fourth, the introduction of micro-insurance schemes modeled on national crop insurance programs can de-risk investments by covering disease-related losses, thereby decreasing reliance on informal lenders and fostering financial stability. Finally, facilitating the formation of Farmer Producer Organizations and digital auction platforms will aggregate supply, stabilize prices, and improve market access—ultimately reinforcing the economic incentives for environmental responsibility. Together, these integrated measures provide a replicable framework for sustainable intensification in emerging aquaculture regions across India and beyond.

Author Contributions:

Conceptualization: Ajay Babu Betala, Avinash Betala.
Data curation: Ajay Babu Betala, Avinash Betala.
Formal analysis: Ajay Babu Betala.
Funding acquisition: Ajay Babu Betala, Avinash Betala.
Investigation: Avinash Betala.
Methodology: Ajay Babu Betala.
Project administration: Avinash Betala.
Resources: Ajay Babu Betala, Avinash Betala.
Software: Avinash Betala.
Visualization: Ajay Babu Betala.
Writing – original draft: Ajay Babu Betala, Avinash Betala.
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