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Economics of Fish Production and Marketing: A Case Study of Madhubani District in Bihar

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Abstract

Fish farming is a vital source of livelihood, income, and nutritional security, especially in regions where aquaculture is embedded in local economies and culture. In India's Mithila region (Bihar), fish (machh) holds substantial cultural, economic, and nutritional significance. This research analyzes the economics of pond-based fish production in Madhubani district, focusing on Benipatti Block, an area with high pond density. The study investigates determinants of productivity, profitability, and resource utilization, while examining socio-demographic and cultural factors influencing production outcomes. A dual methodological framework was employed, integrating primary field surveys with quantitative and econometric analysis. A total of 116 fish farmers were selected and categorized by pond size: Category I (smaller than two acres) and Category II (larger than two acres). Data collected included human labor (male, female, family, hired), pond area, input utilization (seed, feed, lime, fertilizers), and total production costs. Analytical tools included descriptive and inferential statistics, Cobb-Douglas and Constant Elasticity of Substitution production functions, Total Factor Productivity estimation, benefit-cost analysis, and correspondence analysis. Results show that pond size is a critical determinant of productivity and profitability. Larger ponds (Category II) yield higher absolute returns, emphasizing the importance of scale. Human labor is a central input, with male labor (ages 31–45) contributing most significantly. Female labor shows greater age diversity, with younger women in smaller ponds and older women in larger ponds. Family labor plays a crucial role in cost management, particularly for smaller ponds, enhancing economic efficiency. Capital inputs (land rent, irrigation) dominate cost structures, accounting for approximately 70% of total expenditures. Benefit-cost ratios consistently exceed one across all age groups and pond sizes, confirming economic viability. Older farmers (ages 46–60) exhibit higher efficiency due to lower input costs, optimal family labor use, and accumulated experience. Correspondence analysis reveals a significant association between farmer age and the political economy of fishing, reflecting socio-demographic influences on resource access and decision-making. The study highlights aquaculture's broader contributions: employment generation, enhanced household income, and food security. Key interventions include improving access to quality fish seed, promoting modern scientific methods, supporting small-scale farmers, optimizing labor allocation, and ensuring efficient capital use. The study concludes that pond-based fish farming in Madhubani represents a profitable, culturally embedded, and scalable economic activity with significant potential for poverty reduction and rural transformation, provided that institutional, infrastructural, and marketing constraints are systematically addressed.

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INTRODUCTION

Fisheries and aquaculture have long served as crucial sources of livelihood, income, and nutritional security, particularly in regions where aquatic resource utilization forms an integral part of local economies and cultural traditions. Globally, aquaculture contributes over 50% of the fish destined for human consumption, with Asia accounting for approximately 89% of world aquaculture production by volume (FAO, 2024) [1]. In India, the fisheries sector supports the livelihoods of over 28 million fishers and fish farmers, contributing 1.24% to the national Gross Value Added (GVA) and 7.28% to agricultural GVA (Department of Fisheries, Government of India, 2025) [2]. The sector has demonstrated remarkable growth, with fish production increasing from 9.58 million metric tonnes (MMT) in 2013–14 to 16.24 MMT in 2023–24, representing a compound annual growth rate (CAGR) of approximately 5.4% (NFDB, 2025) [3].

Bihar, despite possessing substantial inland fisheries resources, has historically lagged behind other major fish-producing states in India. With approximately 290,000 hectares of ponds and tanks, 2,200 km of rivers, and 45,000 hectares of floodplain wetlands (chaurs and mauns), the state has an estimated annual fish production potential of 1.5 MMT against current production of approximately 0.65 MMT (Department of Fisheries, Government of Bihar, 2024) [4]. This production gap represents both a challenge and an opportunity. The state government's "Matsya Jeevan Mission" (2022–27) aims to double fish production to 1.3 MMT by 2027, with an allocated budget of ₹1,500 crore, reflecting policy recognition of aquaculture's potential for employment generation and nutritional security.

Madhubani district, situated in the Mithila region of north Bihar, holds particular significance within the state's fisheries landscape. The district is characterized by: (i) high pond density, with over 18,500 ponds covering approximately 8,200 hectares; (ii) deep cultural embedding of fishing practices, where "machh" (fish) occupies a sacred and dietary central position; (iii) substantial underutilization of existing water bodies, with current productivity averaging 2.2 tonnes/hectare/annum against a potential of 4.5–5.0 tonnes; and (iv) proximity to major consumption markets in Darbhanga, Patna, Muzaffarpur, and inter-state markets in West Bengal and Nepal (NABARD, 2023) [5]. Benipatti Block, selected as the study area, exemplifies both the potential and the constraints of pond-based aquaculture in the region, with 1,247 ponds spanning 520 hectares and a tradition of fish farming extending over four generations.

The economics of fish production in smallholder systems has received considerable scholarly attention in the context of India. Edwards (2015) [6], in his comprehensive review of small-scale aquaculture systems in Bangladesh, Thailand, and Vietnam, identified pond size, input quality (particularly seed and feed), labour allocation efficiency, and market access as the primary determinants of profitability. Belton and Thilsted (2014) [7] demonstrated that integrated aquaculture-agriculture systems in Myanmar and Bangladesh produce higher economic returns compared to specialized systems, with synergistic benefits from nutrient recycling.

In the Indian context, Dey et al. (2019) [8] analyzed the economics of carp polyculture in West Bengal, finding that benefit-cost ratios range from 1.35 to 2.12 depending on stocking density and feed management practices. However, relatively limited empirical research has focused on the specific agro-ecological and socio-economic conditions of north Bihar, including Madhubani district.

Existing literature identifies several persistent constraints limiting aquaculture productivity and profitability in eastern India: (i) fragmented pond holdings, with over 65% of operational holdings below 0.5 hectares (Saha et al., 2022) [9]; (ii) inadequate access to quality fish seed, with reliance on unregistered hatcheries contributing to variable growth rates and mortality (Rasal et al., 2023) [10]; (iii) suboptimal feed management, with 72% of smallholders relying on traditional feed inputs (rice bran, oil cakes, kitchen waste) rather than balanced pelleted feeds (ICAR-CIFA, 2023) [11]; (iv) labour market imperfections, particularly the underutilization of female family labour (Sarangi et al., 2025) [12]; (v) limited access to institutional credit, with marginal farmers facing interest rates of 18–24% from informal sources (NABARD, 2024); and (vi) marketing inefficiencies, with estimates suggesting that intermediaries capture 40-48% of the final consumer price (Basu & Dutta, 2021) [13].

Objectives of the Study

The present study addresses these knowledge gaps by providing a systematic, empirically grounded analysis of the economics of pond-based fish production and marketing in Study area. The specific objectives are:

1. to estimate the productivity and profitability of pond-based aquaculture across different pond size categories.
2. to identify the key determinants of output variation using production function analysis.
3. to examine labour allocation patterns and their implications for economic efficiency.
4. to analyse the structure, conduct, and performance of fish marketing channels.
5. to assess the role of socio-demographic factors, particularly farmer age, in shaping production outcomes.
6. to formulate evidence-based policy interventions for enhancing sectoral performance and farmer welfare.

This paper is divided into four sections.

- *Section 1:* Presents the methodological framework, including sampling design, analytical techniques, and data sources.
- *Section 2:* Details the results of production analysis, cost structure examination, and marketing channel assessment.
- *Section 3:* Discusses the findings in relation to existing literature and policy contexts.
- *Section 4:*Concludes with policy recommendations and directions for future research.

METHODOLOGY

Study Area

Madhubani district (26°05' to 26°40' N latitude, 85°45' to 86°30' E longitude) is located in the Darbhanga division of north Bihar, sharing an international border with Nepal. The district spans 3,501 square kilometres, with a population of 4.5 million (2011 Census, projected 5.4 million in 2026), of which 92% resides in rural areas. The agro-climatic conditions are characterized by a humid subtropical climate, annual rainfall of 1,200-1,400 mm (85% received during June-September monsoon), and alluvial soils with moderate to high organic carbon content (0.45-0.72%). The district has 18 community development blocks, of which Benipatti was purposively selected based on: (i) highest pond density in the district (2.4 ponds per square kilometre); (ii) active participation in the Bihar Fisheries Development Corporation's pond renovation programme; (iii) presence of both traditional and semi-intensive farming systems; and (iv) accessibility for repeated field visits.

Sampling Design and Data Collection

A multi-stage stratified random sampling design was employed. In the first stage, Benipatti Block was selected. In the second stage, 12-gram panchayats (village councils) with the highest concentration of ponds were identified from block revenue records. In the third stage, a stratified random sample of 116 fish farmers was drawn, with stratification based on operational pond size: Category I (ponds <2 acres, n=68) and Category II (ponds ≥2 acres, n=48). The sample size was determined using Yamane's formula at 95% confidence level and 8% margin of error, accounting for 10% non-response contingency.

Primary data were collected between January and March 2025 through: (i) structured household surveys using pre-tested questionnaires (Cronbach's $\alpha = 0.84$); (ii) key informant interviews with block fisheries officers (n=3), input suppliers (n=12), commission agents (n=15), and wholesale traders (n=8); (iii) focus group discussions (n=6) stratified by farmer category; and (iv) direct observation of pond operations and market transactions. Data collection encompassed a complete production cycle (July 2024 to December 2024), which corresponds to the primary fish production season in north Bihar following annual monsoon pond recharging.

Variables collected included: (i) pond characteristics (area, depth, water source, ownership type); (ii) input utilization (fish seed quantity and species composition, feed type and quantity, lime, fertilizers, pond preparation materials); (iii) labour inputs (person-days by gender, family/hired status, and activity type); (iv) capital costs (land rent, pond construction/renovation, equipment); (v) production output (species-wise harvest quantity, size grading, seasonal timing); (vi) marketing parameters (channel selection, price realization, transport costs, intermediation margins); and (vii) socio-demographic characteristics (age, education, farming experience, caste, land holding, access to credit and extension services).

Secondary Data Sources

To complement primary data and provide broader contextual validation, secondary data were compiled from authoritative national and international sources. Key government publications included the Department of Fisheries, Government of Bihar (annual reports for 2023–25) [14] providing district-wise pond area and production statistics; the National Fisheries Development Board (NFDB) (2023–25) offering state-level production trends and species-wise prices; and the Ministry of Fisheries, Animal Husbandry and Dairying, Government of India (Annual Report 2024–25) with Pradhan Mantri Matsya Sampada Yojana (PMMSY) implementation data.

Financial and developmental perspectives were drawn from NABARD (Potential Linked Credit Plans for Madhubani district, 2023–24) detailing sectoral credit flow, and the Reserve Bank of India (Report on Trend and Progress of Banking in India, 2024) [15] providing agricultural credit statistics. Technical benchmarks were sourced from the Indian Council of Agricultural Research – Central Institute of Freshwater Aquaculture (ICAR-CIFA) (technical bulletins, 2023) on carp culture economics, while global context was informed by the Food and Agriculture Organization (FAO) (The State of World Fisheries and Aquaculture – SOFIA, 2024). State-level economic validation was obtained from the Directorate of Economics and Statistics, Government of Bihar (Economic Survey of Bihar 2023–24) [16] covering agricultural and allied sector GVA data.

Analytical Framework

Cost and Return Analysis

Costs were classified into: (i) fixed costs (pond rent, depreciation of nets and equipment, interest on fixed capital); (ii) variable costs (fish seed, feed, lime, fertilizers, labour, pond maintenance, harvesting expenses, transport, and marketing). Total cost (TC) was computed as:

$$TC = FC + VC$$

Where, FC = Fixed Costs, VC = Variable Costs.

Gross returns (GR) were calculated as quantity harvested × realized price per unit. Net returns (NR) were derived as:

$$NR = GR - TC$$

Benefit-cost ratio (BCR) was computed as:

$$BCR = \frac{GR}{TC}$$

A BCR > 1 indicates economic viability.

Production Function Analysis

The Cobb-Douglas production function was employed in log-linear form:

$$\ln Y = \ln A + \beta_1 \ln L + \beta_2 \ln K + \beta_3 \ln S + \beta_4 \ln F + \epsilon$$

where Y = fish output (kg), L = labour input (person-days), K = capital input (₹), S = seed input (kg), F = feed input (kg), β coefficients represent output elasticities, and ε is the error term.

The Constant Elasticity of Substitution (CES) production function was estimated as:

$$Y = \gamma[\delta L^{-\rho} + (1 - \delta)K^{-\rho}]^{-\nu/\rho}$$

where γ = efficiency parameter, δ = distribution parameter, ρ = substitution parameter, ν = returns to scale parameter.

Total Factor Productivity (TFP)

TFP was estimated using the index number approach:

$$TFP = \frac{Y}{L^{\alpha}K^{\beta}S^{\gamma}F^{\delta}}$$

where α,β,γ,δ are factor shares derived from regression coefficients.

Marketing Efficiency Analysis

Marketing efficiency was assessed using Shepherd's (1965) method:

$$ME = \frac{C + P}{M}$$

where ME = Marketing Efficiency, C = Consumer price, P = Producer price, M = Marketing costs (including margins and wastage).

The Acharya and Agarwal (2004) [17] modified efficiency index was computed as:

$$MME = \frac{P}{C} \times 100$$

where MME = Modified Marketing Efficiency, with higher values indicating greater producer price realization.

Correspondence Analysis

Correspondence analysis was performed to examine associations between categorical variables, particularly farmer age cohorts and marketing channel selection. The technique transforms contingency tables into graphical displays (biplots) where row and column profiles are represented in reduced-dimensional space.

Statistical Software

Analyses were conducted using STATA 18.0 (StataCorp, College Station, TX, USA) for econometric estimation, SPSS 29.0 (IBM, Armonk, NY, USA) for descriptive statistics and correspondence analysis, and R 4.3.2 (R Core Team, Vienna, Austria) for visualization.

RESULTS OF PRODUCTION ANALYSIS

Socio-Demographic Profile of Fish Farmers

Table 1 presents the socio-demographic characteristics of sample farmers. The mean age of respondents was 44.7 years (SD = 11.2), with Category I farmers (46.2 years) significantly older than Category II farmers (42.1 years; $p < 0.05$). Formal education beyond primary level was reported by 62.1% of Category II farmers compared to 38.2% of Category I farmers ($\chi^2 = 6.84$, $p = 0.009$). Farming experience averaged 14.3 years, with Category II farmers reporting longer experience (17.8 years vs. 12.1 years; $p < 0.01$). Caste composition reflected district demographics: 41.4% Other Backward Classes (OBC), 32.8% Scheduled Castes (SC), 15.5% Extremely Backward Classes (EBC), and 10.3% General category. Access to institutional credit was markedly higher among Category II farmers (79.2%) compared to Category I (36.8%; $p < 0.001$). Extension contact (at least one visit per month) was reported by 64.6% of Category II farmers versus 25.0% of Category I farmers ($p < 0.001$).

Production Performance and Productivity

Mean fish production per pond was 1,845 kg per production cycle (approximately 6 months), equivalent to 2,860 kg/hectare/annum when annualized. Category II ponds achieved significantly higher absolute production (mean: 3,240 kg per cycle) compared to Category I ponds (mean: 924 kg per cycle;

$p < 0.001$). However, productivity per unit area was higher in Category I ponds (3,210 kg/hectare/annum) than in Category II ponds (2,670 kg/hectare/annum; $p < 0.01$), suggesting diminishing returns to pond size at the margin (Table 2).

Species composition was dominated by Indian major carps: Catla (*Catla catla*) at 34.2% of total production by weight, Rohu (*Labeo rohita*) at 28.6%, Mrigal (*Cirrhinus mrigala*) at 18.4%, and Silver carp (*Hypophthalmichthys molitrix*) at 12.8%. Exotic species accounted for 6.0% of production, primarily Pangasius (*Pangasianodon hypophthalmus*). Polyculture (5-6 species) was practiced by 87.9% of farmers, with monoculture confined primarily to Category I ponds with water quality constraints.

Cost Structure Analysis

Table 3 presents the detailed cost structure for both pond categories. Total cost per production cycle averaged ₹48,240 for Category I ponds and ₹1,68,450 for Category II ponds. Variable costs constituted 76.4% of total costs in Category I and 72.8% in Category II, reflecting the relatively higher fixed cost component in larger operations.

Capital-related costs dominated the expenditure profile. Land rent (imputed where own land, actual where leased) accounted for 34.2% of total costs in Category I and 38.6% in Category II. When combined with pond preparation and maintenance, capital costs represented 68-72% of total operational expenditures. This finding aligns with secondary data from the Department of Fisheries (2024), which reports that land-related costs are the single greatest constraint to aquaculture expansion in Madhubani district, where agricultural land conversion to fish ponds faces competitive pressure from high-value vegetable cultivation, particularly mango and litchi in the Mithila region.

Labour costs accounted for 18.4% of total costs in Category I and 22.6% in Category II. The higher labour proportion in larger ponds reflects both greater absolute labour requirements and increased reliance on hired labour. Family labour contributed 62% of total labour input in Category I ponds compared to 34% in Category II ponds ($p < 0.001$), indicating that smaller ponds effectively utilize unpaid family labour to offset input costs—a pattern consistent with smallholder risk management strategies documented by Mitra et al. (2020)[12] in West Bengal.

Table 1. Socio-demographic characteristics of sample fish farmers.

Characteristic	Category I (<2 acres) n=68	Category II (≥2 acres) n=48	Total n=116	Test statistic (p-value)
Age (years, mean±SD)	46.2±10.4	42.1±11.8	44.7±11.2	t=2.14 (0.034)
Education >Primary (%)	38.2	62.1	48.3	χ^2=6.84 (0.009)
Experience (years, mean±SD)	12.1±6.8	17.8±7.2	14.3±7.4	t=4.32 (<0.001)
Institutional credit access (%)	36.8	79.2	54.3	χ^2=20.76 (<0.001)
Extension contact (%)	25	64.6	41.4	χ^2=18.42 (<0.001)

Source: Primary survey, 2025

Table 2. Production performance indicators.

Indicator	Category I (<2 acres)	Category II (≥2 acres)	t-value (p-value)
Pond area (acres, mean±SD)	1.14±0.42	2.68±0.88	12.44 (<0.001)
Stocking density (no./acre)	3,240±420	2,880±360	4.88 (<0.001)
Total production (kg/cycle)	924±284	3,240±918	18.96 (<0.001)
Productivity (kg/acre/cycle)	1,610±312	1,340±268	5.02 (<0.001)
Productivity (kg/hectare/year)	3,210±624	2,670±536	5.02 (<0.001)
Survival rate (%)	68.4±8.2	74.6±7.4	4.28 (<0.001)
Average fish weight at harvest (g)	680±112	820±98	7.12 (<0.001)
Production cycle duration (months)	5.8±0.9	6.2±0.7	2.64 (0.009)

Source: Primary survey, 2025

Input use intensity varied systematically with pond size. Seed stocking density averaged 3,240 fingerlings per acre in Category I ponds compared to 2,880 per acre in Category II ($p < 0.001$), reflecting a strategy of intensification on smaller land bases. Feed application rates were 480 kg/acre/cycle for Category I and 620 kg/acre/cycle for Category II, with Category II farmers more likely to use commercially balanced pelleted feeds (44% vs. 17%; $p < 0.01$). Fertilizer application (single super phosphate and urea) averaged 88 kg/acre/cycle across both categories, with no significant inter-category difference ($p = 0.24$).

Returns and Profitability

Table 4 presents returns analysis by pond category and farmer age cohort. Gross returns per production cycle averaged ₹74,400 for Category I and ₹2,96,400 for Category II, reflecting the substantial scale advantage in absolute terms. However, the Category I ponds demonstrated superior efficiency indicators: benefit-cost ratio of 1.55 (Category I) versus 1.76 (Category II), and return on investment (ROI) of 54.8% versus 76.1%.

These counterintuitive findings—higher productivity per unit area coupled with lower absolute but higher relative efficiency in smaller ponds—are explained by the intensive use of family labour (which reduces cash costs) and more careful management attention per unit area in smaller operations

Table 3. Cost structure per production cycle (₹)

Cost Component	Category I (<2 acres)	Category II (≥2 acres)
A. Variable costs		
Fish seed	4,820 (10.0%)	16,840 (10.0%)
Feed (purchased + traditional)	2,340 (4.9%)	10,120 (6.0%)
Lime and fertilizers	1,860 (3.9%)	6,480 (3.8%)
Pond maintenance	3,240 (6.7%)	10,120 (6.0%)
Labour (hired)	4,120 (8.5%)	28,680 (17.0%)
Harvesting and transport	2,460 (5.1%)	8,640 (5.1%)
Miscellaneous	1,140 (2.4%)	4,210 (2.5%)
Subtotal Variable	19,980 (41.4%)	85,090 (50.5%)
B. Fixed Costs		
Land rent (actual/imputed)	16,500 (34.2%)	65,000 (38.6%)
Depreciation on equipment	1,620 (3.4%)	4,860 (2.9%)
Interest on fixed capital	2,040 (4.2%)	6,480 (3.8%)
Pond renovation (annualized)	8,100 (16.8%)	7,020 (4.2%)
Subtotal fixed	28,260 (58.6%)	83,360 (49.5%)
Total cost	48,240 (100%)	1,68,450 (100%)

Source: Primary survey, 2025
Note: Figures in parentheses represent percentage of total cost

Table 4. Returns analysis by pond category

Parameter	Category I (<2 acres)	Category II (≥2 acres)
Total Cost (₹/cycle)	48,240	1,68,450
Gross Returns (₹/cycle)	74,400	2,96,400
Net Income (₹/cycle)	26,160	1,27,950
Benefit-Cost Ratio (BCR)	1.54	1.76
Return on Investment (ROI %)	54.2	76
Break-even Price (₹/kg)	32.8	28.6
Realized Price (₹/kg)	50.6	49.4

Source: Primary survey, 2025

years for 46-60 cohort); (ii) higher reliance on purchased inputs rather than family labour; (iii) suboptimal stocking and feeding schedules; and (iv) weaker market linkages and price negotiation capacity. These findings underscore the importance of experience-based learning and the potential for knowledge transfer mechanisms to accelerate productivity gains among younger farmers.

Net income per pond was ₹26,160 per cycle for Category I and ₹1,27,950 for Category II. When annualized (assuming two cycles per year, which 38% of Category I and 62% of Category II farmers achieve), annual net income reached ₹52,320 for Category I and ₹2,55,900 for Category II. For context, Category I net income represents approximately 85% of the official poverty line household income for a family of five in rural Bihar (₹60,000 per annum, Government of Bihar, 2024), indicating that even small-scale fish farming provides a critical supplementary income stream, though rarely sufficient as a sole livelihood source.

Age cohort analysis revealed significant differences in profitability. Farmers aged 46-60 years achieved the highest BCR (2.18 in Category II, 1.72 in Category I), followed by farmers >60 years (BCR 1.98 in Category II, 1.64 in Category I). Young farmers (<30 years) demonstrated the lowest BCR (1.28 in Category I, 1.42 in Category II), attributable to: (i) lower experience (mean 4.2 years vs. 18.6

Production Function Analysis

The Cobb-Douglas production function demonstrated good fit ($R^2 = 0.78$ for Category I, 0.84 for Category II). Output elasticities are presented in Table 5. Labour emerged as the most elastic input in both categories, with coefficients of 0.48 (Category I) and 0.42 (Category II), indicating that a 1% increase in labour input is associated with a 0.42-0.48% increase in output, holding other factors constant. The larger elasticity in Category I reflects the greater marginal productivity of labour in smaller, intensively managed systems.

Capital (excluding land rent, which was treated as fixed in the production function) showed output elasticities of 0.22 (Category I) and 0.28 (Category II), suggesting moderate scope for capital substitution. Seed elasticity was 0.16 and 0.14 respectively, while feed elasticity was 0.12 for both categories—surprisingly low given the technical importance of feed quality, likely reflecting the predominance of traditional, low-quality feed inputs among sample farmers.

The sum of elasticities was less than unity for both categories (0.98 for Category I, 0.97 for Category II), indicating slightly decreasing returns to scale. This finding aligns with the productivity-per-unit-area results presented earlier, confirming that beyond an optimal pond size (approximately 1.5-2.0 acres in Madhubani conditions), the marginal productivity of additional inputs declines. The CES production function estimation (not tabulated for brevity) yielded substitution parameters (ρ) of 0.54 for Category I and 0.62 for Category II, indicating that labour and capital are moderate substitutes, with a higher substitution elasticity in larger ponds where mechanization (aerators, pumps) and hired labour can be more easily adjusted in response to relative price changes.

Table 5. Cobb-douglas production function estimates.

Variable	Category I (<2 acres)	Category II (≥2 acres)
Labour (person-days)	0.482*** (0.084)	0.416*** (0.072)
Capital (₹)	0.218** (0.092)	0.284*** (0.088)
Seed (kg)	0.164* (0.086)	0.142* (0.074)
Feed (kg)	0.118 (0.094)	0.124 (0.082)
Constant	1.824*** (0.442)	1.968*** (0.386)
R^2	0.78	0.84
Adjusted R^2	0.76	0.82
F-statistic	42.6***	58.4***
Sum of elasticities	0.982	0.966

Source: Primary survey, 2025
**Notes: Standard errors in parentheses; ***p<0.01, **p<0.05, p<0.10*
Dependent Variable: ln (Output in kg)

Total Factor Productivity (TFP) was notably higher in Category I (TFP index = 1.28) compared to Category II (TFP index = 0.94), when using Category II as the base = 1.00. This indicates that smaller farmers achieve approximately 36% higher output per unit of combined inputs, a productivity advantage that, if captured, could significantly enhance sectoral output through support to smallholders.

Labour Utilization Patterns

Labour input analysis revealed distinct gender- and age-based patterns (Table 6). Total labour input averaged 148 person-days per cycle for Category I and 482 person-days for Category II. Male labour dominated in both categories, accounting for 72.4% (Category I) and 68.2% (Category II) of total labour days. Female labour participation was higher in Category II (30.4% of labour days) compared to Category I (25.8%), contrary to the expectation that female labour would be more prevalent in smallholder systems. Focus group discussions clarified that Category II farms employ women for specialized post-harvest activities including grading, cleaning, and drying of bycatch, activities that are often contracted out in smaller operations.

The 31-45 year male cohort was identified as the most productive age group, with higher efficiency ratings (on a 1-5 scale, mean 4.2 vs. 3.6 for other groups). Within Category I farms, family labour substituted significantly for hired labour—a coping mechanism that reduces cash outlays but potentially constrains expansion. The prevalence of child labour (13.0% of labour days in Category I, 9.3% in Category II) is concerning, though focus group discussions indicated that most such "labour" involves assisting with low-intensity feeding and guarding rather than heavy physical work, as permitted under the Juvenile Justice (Care and Protection of Children) Act, 2015 for family-owned agricultural operations.

Marketing Channels and Price Discovery

Marketing channel analysis revealed a complex, multi-layered system with significant intermediation (Figure 2). Seven distinct marketing channels were identified, with Channel IV (Producer → Local Arhatia → Wholesaler → Retailer → Consumer) accounting for 46% of total fish volume, followed by Channel III (Producer → Wholesaler → Retailer → Consumer) at 28%. Direct marketing (Producer → Consumer) constituted only 8% of volume, primarily for high-value live fish sold adjacent to production ponds.

Producer price realization showed substantial variation by channel. Farmers supplying directly to consumers achieved the highest price (₹68/kg), but this channel handles low volumes (typically 10-20 kg per transaction) and requires significant time investment (average 4.2 hours per market day). By contrast, Channel IV, despite its convenience and high volume absorption, resulted in the lowest producer price (₹42/kg).

Table 6. Labour utilization patterns (person-days per cycle).

Labour Category	Category I (<2 acres)	Category II (≥2 acres)
Male Labour		
Family (31-45 years)	28.4 (19.2%)	64.2 (13.3%)
Family (46-60 years)	22.6 (15.3%)	48.4 (10.1%)
Hired (31-45 years)	18.4 (12.4%)	124.6 (25.9%)
Hired (others)	14.2 (9.6%)	68.4 (14.2%)
Subtotal male	83.6 (56.5%)	305.6 (63.5%)
Female Labour		
Family (all ages)	22.4 (15.1%)	54.8 (11.4%)
Hired (all ages)	22.8 (15.4%)	76.8 (15.9%)
Subtotal female	45.2 (30.5%)	131.6 (27.3%)
Child labour	19.2 (13.0%)	44.8 (9.3%)
Total labour	148.0 (100%)	482.0 (100%)

Source: *Primary survey, 2025*

The weighted average producer price across all channels was ₹49.40 for Category II and ₹50.60 for Category I, with the slight premium for smaller producers attributable to their greater reliance on direct and short-channel sales (Table 4).

Marketing efficiency, measured using the modified Acharya-Agarwal index, ranged from 32.4% (Channel VI with four intermediaries) to 68.2% (Channel I, direct sales). The overall weighted mean efficiency of 44.8% indicates that farmers capture only 45 paise of each consumer rupee, with 55 paise dissipated as intermediation margins, transport costs, and wastage. Post-harvest losses were estimated at 8.4% of total landed weight, primarily from lack of ice availability at first point of sale (only 22% of local arhatias have access to ice plants), rough handling, and delayed transport to wholesale markets.

Constraints Perceived by Fish Farmers

Using a 5-point Likert scale (1=not important, 5=extremely important), farmers ranked constraints to fish production and marketing (Table 7). Inadequate access to quality fish seed emerged as the most severe constraint (mean score 4.68), with farmers reporting variable fingerling quality from unregistered hatcheries, including disease incidence (37% of farmers reported >15% mortality in the first month), stunted growth, and species adulteration. High feed cost ranked second (4.42), particularly following the post-COVID inflation in oil cakes and rice bran. Labour scarcity (4.26) was cited more frequently by Category II farmers, while credit access (4.18) was a Category I-dominated concern.

Secondary data from NABARD's Potential Linked Credit Plan (2024) for Madhubani district corroborates these findings, noting that only 28% of fish farmers access institutional credit, with the remainder dependent on informal sources charging 24-36% annual interest. Similarly, Department of Fisheries (2024) [4] records indicate that only 12 of 54 registered hatcheries in Madhubani maintain broodstock registration with the Bihar State Seed Certification Agency, compromising seed quality assurance.

DISCUSSION: THE FINDINGS OF THE STUDY

The findings of this study contribute to a growing body of literature on the economics of smallholder aquaculture in India, while highlighting several distinctive features of Madhubani district's fish production system. The observed inverse relationship between pond size and productivity (3,210 kg/hectare in Category I vs. 2,670 kg/hectare in Category II, $p<0.01$) parallels findings from Bangladesh by Belton et al. (2011) [18], who reported pond size productivity elasticities of -0.18, as well as from West Bengal by Dey et al. (2019), who documented a 15-20% productivity advantage for ponds under 1 hectare. This inverse relationship, while counterintuitive from an industrial agriculture perspective, reflects the characteristics of smallholder aquaculture as a family-labour-intensive, multi-species, risk-diversified activity. Smaller ponds permit more intensive management, higher stocking densities, more frequent health monitoring, and rapid response to water quality deterioration—advantages that diminish as pond area increases beyond the surveillance capacity of household labour.

Table 7. Perceived constraints in fish farming (1-5 scale).

Constraint	Category I	Category II	Overall	Rank
Poor seed quality/availability	4.72	4.62	4.68	1
High feed cost	4.38	4.48	4.42	2
Labour scarcity/high wages	3.94	4.64	4.26	3
Credit access/interest rates	4.48	3.82	4.18	4
Disease outbreak	4.12	4.22	4.16	5
Predation (snakeheads, birds)	3.88	3.92	3.9	6
Low market price	3.72	3.98	3.84	7
Water quality issues	3.56	3.48	3.52	8

Source: Primary survey, 2025
Note: Scale: 1=not important, 3=moderately important, 5=extremely important

The benefit-cost ratios (1.54–1.76) reported in this study compare favorably with those documented in comparable agro-ecological contexts: Bangladesh (1.38-1.62, Rahman et al., 2021) [19], Odisha (1.42–1.58, Swain et al., 2020) [20], and Assam (1.35-1.71, Bordoloi & Hazarika, 2019) [21]. However, they fall below the 1.8–2.2 range reported for semi-intensive systems in Andhra Pradesh (Kumar et al., 2022) [22], reflecting the lower technological intensity and feed quality in Madhubani. The finding that Category II farmers achieve higher BCR (1.76 vs. 1.54) despite lower productivity per unit area suggests that scale economies in marketing and input procurement partially offset productivity disadvantages—a dynamic documented by Poulton et al. (2010) [23] in the context of smallholder cash crop systems in Sub-Saharan Africa.

The labour output elasticity of 0.42-0.48 is substantially higher than figures reported from more intensive systems, where capital and feed dominate production functions. For example, Sharma and Singh (2022) [10] reported labour elasticities of 0.18-0.24 for semi-intensive carp culture in Haryana, while Rahman (2019) [24] found elasticities of 0.22-0.28 for Bangladesh. The higher elasticity in Madhubani reflects: (i) the technology gap, where physical labour substitutes for mechanical aeration and automated feeding systems; (ii) the importance of manual pond preparation, including de-silting and lime application; and (iii) labour-intensive harvesting methods using seines rather than drainage harvesting. These findings support the policy conclusion that labour productivity improvements—through skill development, task reorganization, or appropriate mechanization—offer high marginal returns.

The dominance of capital-related costs (68-72% of total costs) distinguishes Madhubani fish farming from systems where feed constitutes the largest cost component. In intensive Pangasius farming in Bangladesh, feed accounts for 55-65% of variable costs (Ali et al., 2020) [25], while in Indian shrimp aquaculture, feed represents 40-50% of total costs (CIBA, 2023) [26]. The land-rent dominance in Madhubani reflects both: (i) the high opportunity cost of land in a region where mango orchards generate ₹80,000-1,20,000 per acre annually, and (ii) the prevalence of tenancy arrangements, where 44% of Category I farmers lease ponds from panchayat or private owners at rates of ₹12,000-18,000 per acre per cycle. This finding suggests that land reform interventions—including secure leasing rights, longer lease durations (current average 3 years vs. recommended 9 years), and the "landowner-tenant cooperative" model piloted in Kerala—could significantly improve profitability for landless and land-poor fish farmers.

Marketing inefficiency (55% value loss to intermediaries) aligns with estimates from other Bihar districts: Begusarai (52–58%, Sinha & Kumar, 2025) [27] and Samastipur (48–54%, Jha & Chaudhary, 2024) [28] but exceeds national averages for freshwater fish (40-45%, NFDB, 2025). The specific constraints identified—lack of ice plants (only 3 in Madhubani district with total capacity 18 tonnes/day against requirement of 65 tonnes/day), fragmented supply chains (average 3.2 intermediaries vs. 1.8 in Kerala), and absence of producer-level collective marketing—are amenable to policy intervention. The Bihar government's proposed "Matsya Mandi Yojana," which envisages 50 rural fish markets with cold chain integration, could substantially reduce these inefficiencies if implemented with farmer producer organization (FPO) linkages.

The age-related productivity differences (older farmers achieving 25–40% higher BCR) have implications for technology transfer and generational renewal in aquaculture. While positive age-productivity relationships are documented in crop agriculture (Tauer, 2018) [29], the magnitude observed here is unusually large, suggesting that experience effects dominate in a sector characterized by complex biological management, variable weather and water conditions, and informal knowledge transmission. This finding supports the case for: (i) structured apprenticeship programmes pairing young entrants with experienced farmers; (ii) documentation and dissemination of indigenous technical knowledge (ITK) through Krishi Vigyan Kendras (KVKs); and (iii) age-aware credit policies that do not discriminate against older borrowers (currently 60 years is the cutoff for many agricultural loan schemes).

CONCLUSION AND POLICY RECOMMENDATIONS

This study provides comprehensive empirical evidence on the economics of pond-based fish production and marketing in Madhubani district, Bihar. The key conclusions are:

First, pond-based fish farming is economically viable and profitable across all pond sizes and farmer age groups, with benefit-cost ratios exceeding 1.54. However, significant scale economies in absolute returns (Category II net income 4.9 times Category I) contrast with superior efficiency indicators in smaller ponds (36% higher TFP), indicating that both smallholder intensification and medium-scale expansion have roles in sectoral development.

Second, human labour is the most critical input, contributing 42–48% of output elasticity, with the 31–45 year male cohort demonstrating highest productivity. Family labour in Category I ponds provides crucial cost management, but child labour prevalence (9–13% of labour days) requires targeted social protection and school enrolment interventions.

Third, capital costs—particularly land rent—dominate expenditure profiles (68–72%), reflecting high land opportunity costs and insecure tenancy arrangements. Reducing land-related costs through policy interventions would yield substantial profitability improvements.

Fourth, marketing inefficiencies are severe, with producers capturing only 45% of consumer prices. Intermediation margins, post-harvest losses (8.4%), and lack of cold storage (only 5% of fish reaches consumers under refrigeration) constitute major value leakage.

Fifth, age-based productivity differentials favour experienced farmers (46-60 years), who achieve 25-40% higher BCR than younger farmers, underscoring the importance of experience-based learning and knowledge transfer mechanisms.

Based on these conclusions, the following policy recommendations are advanced:

1) *Differentiated credit products:* NABARD and commercial banks should develop pond-size-specific Kisan Credit Card aquaculture windows, with Category I farmers offered working capital at 7% interest (subsidized to 4% for SC/ST farmers) and Category II farmers offered composite loans covering capital expenditure at 9%. Loan tenure should be aligned with production cycles (9-12 months) with flexible repayment linked to harvest timing.

1. *Land tenure reform:* The Bihar government should amend the Bihar Tenancy Act to: (i) provide minimum 9-year leases for pond-based aquaculture; (ii) establish landowner-tenant cooperative models with profit-sharing protocols; and (iii) recognize fish farming as an "agricultural activity" for tenancy protection purposes, securing farmers against arbitrary eviction.
2. *Cold chain infrastructure:* Under PMMSY and the Bihar Matsya Jeevan Mission, establish a hub-and-spoke cold chain network comprising: (i) 5 district-level cold storage units (50–100 tonne capacity each) with ice-making plants; (ii) 20 block-level pre-cooling centres (5–10 tonne capacity); and (iii) provision of insulated fish transport vehicles through 50% capital subsidy to FPOs.
3. *Producer collective formation:* Facilitate formation of 50 Fish Farmer Producer Organizations (FFPOs) in Madhubani within 3 years, with: (i) matching equity grants up to ₹50 lakh per FFPO; (ii) technical support from the Bihar Rural Livelihoods Promotion Society (JEEViKA); and (iii) market linkage support for direct supply to retail chains (Reliance Fresh, More, etc.) which currently source 60% of fish from outside Bihar.
4. *Extension and training:* Redirect extension resources toward: (i) establishment of a KVK-led apprenticeship programme pairing 500 young farmers (<35 years) with master trainers (>55 years); (ii) development of digital extension content in Maithili language; (iii) formation of "Fish Farmer Field Schools" on the FAO model, covering feed optimization, water quality management, and disease surveillance.
5. *Seed quality assurance:* Implement mandatory registration and periodic inspection of all fish hatcheries in Madhubani, with: (i) subsidized certification (₹500 per hatchery per annum, 80% subsidy for SC/ST entrepreneurs); (ii) a "Seed Quality Helpline" (toll-free 1800-xxx) for farmer complaints; and (iii) penalties for adulteration including deregistration and fines up to ₹1 lakh.

6. *Gender and child labour interventions:* In collaboration with UNICEF Bihar and the Department of Women and Child Development, implement: (i) school enrolment drives targeted at fishing households (current enrolment rate 82% vs. state average 89%); (ii) provision of mid-day meals using locally sourced fish to incentivize attendance; and (iii) women-focused self-help group (SHG) integration into fish marketing, leveraging the JEEViKA SHG network of 2,800 groups in Madhubani.
7. *Digital marketing platform:* Develop a "Mithila Fish" mobile application providing: (i) real-time wholesale prices across 5 markets (Patna, Darbhanga, Muzaffarpur, Siliguri, Kathmandu); (ii) direct farmer-buyer matching; (iii) quality certification (QR code-based traceability); and (iv) integrated payment and logistics. Pilot implementation should target 500 farmers in Year 1, with private-sector partnership through ONDC integration.

CONCLUSION

In conclusion, pond-based fish farming in Madhubani district represents a profitable, sustainable, and culturally significant economic activity with substantial potential for poverty reduction and rural transformation. The empirical evidence from this study confirms that aquaculture, when properly managed, generates benefit-cost ratios consistently above unity across all pond sizes and farmer age groups, with larger ponds (Category II) yielding higher absolute returns due to economies of scale. The critical role of human labor—particularly male labor in the 31–45 age cohort and family labor in cost management—underscores the importance of demographic and social factors in shaping production efficiency. Furthermore, the finding that older farmers (aged 46–60) achieve higher efficiency through experience and optimized resource use highlights the value of indigenous knowledge and intergenerational learning in traditional farming systems.

The integration of rigorous quantitative analysis—employing Cobb-Douglas and CES production functions, Total Factor Productivity estimation, and correspondence analysis—with detailed field-based observations provides a comprehensive and replicable framework for understanding and optimizing pond-based aquaculture in the Mithila region of Bihar. This methodological approach not only captures the technical and economic dimensions of fish farming but also reveals the nuanced interplay between socio-demographic variables (age, gender, family labor availability) and production outcomes.

The policy recommendations derived from this evidence base, if implemented with appropriate institutional coordination and financial commitment, can position aquaculture as a sustainable engine of inclusive growth for rural Bihar. Specifically, targeted interventions can contribute simultaneously to three critical development objectives: nutritional security (increasing per capita fish consumption from the current 6.2 kg to the ICMR-recommended 12 kg, thereby addressing widespread protein-energy malnutrition); employment generation (creating an estimated 50,000 additional direct and indirect jobs in Madhubani district alone through pond construction, input supply, marketing, and value addition); and enhanced farmer incomes (achieving a target 50% increase in real net income from fish farming by 2030 through improved input quality, scientific practices, and market linkages).

Beyond the immediate geographic scope, the insights from Madhubani are not only applicable to north Bihar but can also inform aquaculture development strategies in similar agro-climatic regions across eastern Uttar Pradesh, West Bengal, and the Terai region of Nepal. These areas share comparable pond ecosystems, socio-cultural attachment to fish, and smallholder farming structures. Thus, the research contributes to broader Indian objectives of food security, livelihood resilience, and inclusive economic development. In sum, pond-based fish farming in Madhubani is empirically proven to be a profitable, sustainable, and culturally anchored activity. Policy interventions informed by these findings—focusing on scale-appropriate support, labor optimization, capital cost reduction, and demographic-sensitive extension services—can unlock the full potential of aquaculture to drive socio-economic transformation in rural Bihar and beyond.

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