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TECHNOLOGY ADOPTION AND PROFITABILITY IN MAKHANA CULTIVATION: DETERMINANTS, BARRIERS, AND POLICY LEVERS IN BIHAR

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ABSTRACT

Makhana (Euryale ferox Salisb.), commonly known as fox nut, is an aquatic crop predominantly cultivated in Bihar, India, which accounts for approximately 85-90 percent of global production. This study synthesises secondary data and literature to examine technology adoption in makhana cultivation and its impact on farm profitability. Technology adoption is conceptualised as a multi-component package encompassing improved planting materials, pond preparation, water management, mechanised weeding, nutrient and plant protection practices, enhanced drying and processing, grading and packaging, digital market information, and institutional innovations like producer groups. The synthesis highlights determinants such as household education, asset endowments, extension services, and market access, while quantifying profitability through metrics like gross margins and benefit-cost ratios. Barriers including credit constraints, input quality issues, information gaps, risk, and infrastructure deficiencies are diagnosed. The narrative is grounded in an economics-of-adoption framework emphasising information, incentives, and transaction costs. Findings suggest that higher adoption correlates with improved yields and net returns, though endogeneity challenges persist. Policy levers focus on targeted extension, credit products, subsidies, and market reforms to enhance Bihar's makhana sector sustainability and equity.

Keywords: Makhana cultivation, technology adoption, farm profitability, Bihar agriculture, policy levers, value chain

INTRODUCTION

Makhana cultivation represents a vital component of Bihar's agricultural economy, contributing significantly to rural livelihoods in waterlogged and flood-prone regions. Bihar dominates global makhana production, with an estimated 35,000-40,000 hectares under cultivation and annual seed output exceeding 56,000 metric tonnes [1]. This crop, valued for its nutritional properties, including high protein and mineral content, supports thousands of resource-poor households, particularly in districts like Madhubani, Darbhanga, Purnea, and Katihar [2]. Despite its potential, adoption of modern technologies remains uneven, impacting profitability and sector growth [3]. This study explores the determinants of technology adoption, its linkage to profitability, barriers faced by cultivators, and actionable policy levers.

Technology adoption in makhana is defined as the uptake of a multi-component package. Plot-level production technologies include improved seed varieties like Swarna Vaidehi or Sabour Makhana-1, optimised pond preparation with liming and fertilisation, efficient water management to maintain 1-2 metre depths, mechanised or manual weeding to control aquatic weeds, recommended nutrient applications (e.g., 60:40:20 kg NPK/ha), and integrated pest management for issues like leaf blight [4]. Post-harvest technologies encompass solar or mechanical drying to reduce moisture to 10-12 percent, improved roasting and popping methods yielding 35-40 percent efficiency, and standardised grading into categories like lava (popped kernels) [5]. Market and digital technologies involve mobile apps for price information, e-marketing platforms, and institutional arrangements such as farmer producer organisations (FPOs) for collective bargaining [6]. Distinguishing these domains is crucial, as production technologies directly affect yields, while post-harvest and market ones influence price realisation and losses.

The economics-of-adoption framework posits that farmers adopt technologies when expected benefits exceed costs, moderated by information asymmetries, risk perceptions, and constraints [7]. In Bihar, where smallholders predominate, adoption enhances profitability through higher yields (up to 3-3.5 t/ha in improved systems versus 1.7-2 t/ha traditionally), cost reductions, and better quality premiums [8]. However, empirical evidence on these relationships is fragmented, necessitating a synthesis approach.

STUDY CONTEXT (MAKHANA CULTIVATION AND THE BIHAR VALUE CHAIN)

Bihar's agro-climatic conditions, characterised by alluvial plains and abundant wetlands, make it ideal for makhana cultivation. The state spans four agro-climatic zones, with Zone I (North Alluvial Plain) and Zone II (North East Alluvial Plain) hosting most production due to annual rainfall of 1,040-1,700 mm and sandy loam soils [9]. Cultivation occurs in two systems: traditional pond-based, covering about 70 percent of the area, and emerging field-based in low-lying paddies, which offers higher yields but requires controlled irrigation [10]. Major districts contribute variably; for instance, Purnea and Katihar lead in yield (2.5-3 t/ha), while Darbhanga and Madhubani dominate area but show moderate productivity [11].

The value chain begins with seed collection from perennial water bodies, followed by nursery raising and transplanting in March-April. Harvesting spans August-November, involving labour-intensive diving for seeds [12]. Processing, primarily manual, converts seeds to popped makhana with 35 percent efficiency, generating employment for over 50,000 households, many from the Mallah community [13]. Marketing channels include farmer-processor-retailer-consumer (most efficiently) longer chains with wholesalers, where farmers capture 55-60 percent of the retail price [14]. Exports, though growing at 11 percent annually to reach USD 21 million in 2017-18, remain under 1 percent of production, targeting the USA, UK, and Gulf countries [15]. Bihar's chain faces inefficiencies like high post-harvest losses (10-15 percent) and limited mechanisation, underscoring the need for adoption-driven improvements [16].

LITERATURE REVIEW

Early studies on makhana economics highlight its role in wetland utilisation, with Bihar's production monopoly yielding net returns of Rs. 14,000-19,000/ha [17]. Adoption literature reveals low uptake of scientific practices; for example, only 85 percent of farmers integrate makhana-fish culture, but knowledge gaps persist in nutrient management (61 percent gap) [18]. Determinants include education (positive correlation with adoption), asset base like pond access, and extension exposure [19]. Profitability analyses show adopters achieving 20-30 percent higher gross margins due to yield gains and cost efficiencies [20].

Barriers are well-documented: credit constraints limit input access, with 57 percent of processors citing machinery shortages [21]. Information frictions and risk from floods deter investment, while tenancy insecurity affects 40 percent of cultivators leasing ponds [22]. Value chain studies emphasise transaction costs and market power of intermediaries, reducing farmer shares [23]. Policy-orientated research advocates subsidies and FPOs, as seen in the Makhana Vikas Yojana, which expanded the area by 40-50 percent from 2020 to

2025 [24]. Globally, FAO notes makhana's potential as a climate-resilient crop, akin to other aquatic nuts [25]. This synthesis builds on these by integrating domains and proposing levers.

CONCEPTUAL FRAMEWORK

The framework draws from economics-of-adoption theory, incorporating information and learning (e.g., extension reduces knowledge gaps), constraints and incentives (credit and subsidies lower barriers), risk and uncertainty (insurance mitigates flood losses), transaction costs (FPOs reduce marketing frictions), and value chain governance (standards improve price realisation) [26]. The causal pathway from adoption to profitability operates via mechanisms: production technologies boost yields by 20-50 percent and quality (e.g., uniform popping); post-harvest reduces losses by 10 percent; market technologies enhance prices by 15-20 percent through better grading and information [27]. Endogeneity arises as profitable farmers may self-select into adoption, necessitating corrections like propensity score matching [28]. Overall, adoption shifts the production function upward, increasing net returns per hectare.

DATA & SAMPLING DESIGN

This study employs a secondary-data and literature synthesis approach, as publicly available microdata on makhana households is limited. Sources include Government of Bihar horticulture statistics, ICAR reports, NABARD value chain analyses, peer-reviewed journals, and institutional documents from FAO and the World Bank [29]. District-level aggregates anchor the analysis in Bihar's key zones: traditional (Darbhanga, Madhubani) and emerging (Purnea, Katihar). Sample profiles are proxied from surveys in these areas, e.g., 120 farmers across regions with average holdings of 1-2 ha [30]. Econometric estimates are presented as illustrative frameworks without reported coefficients, drawing from meta-analyses of similar studies. Limitations include potential aggregation bias and outdated proxies for district estimates where makhana-specific data is absent.

VARIABLES & MEASUREMENT

Adoption outcomes are measured multidimensionally. Binary adoption indicates uptake of at least one technology (e.g., improved seeds). The intensity index counts adopted practices (0-10 scale across domains). Domain indices aggregate production (seeds, nutrients, pests; 0-5), post-harvest (drying, popping; 0-3), and marketing/digital (apps, FPOs; 0-2) [31]. Profitability outcomes include gross margin (revenue minus variable costs), net returns (gross margin minus fixed costs), and benefit-cost ratio (total revenue/total costs). Costs encompass labour (Rs. 32,000-33,000/ha), inputs (Rs. 10,000/ha), and rent (Rs. 7,500-17,500/ha); revenue from seed sales is at Rs. 150-200/kg [32]. Controls include household size, education, pond access, and market distance; confounders like flood exposure are noted.

ECONOMETRIC STRATEGY

A two-part strategy is illustrative. Part A models adoption: logit for binary

$$P(Adopt = 1|X) = \frac{1}{1 + e^{-(\beta_0 + \beta X)}},$$

reporting marginal effects; Poisson for intensity count [33]. Part B regresses profitability on adoption:

$$Profit = \alpha + \gamma Adopt + \delta Z + \epsilon,$$

addressing endogeneity via propensity score matching (PSM) to balance covariates between adopters and non-adopters [34]. Robustness includes alternative measures (e.g., B:C ratio), domain-specific adoption, and district fixed effects. Without instruments, IV is avoided; qualitative sensitivity discusses omitted variables like risk preferences.

RESULTS

Synthesis reveals average adoption rates of 50-60 percent for production technologies, lower for post-harvest (30-40 percent) due to mechanisation gaps [35]. Profitability averages Rs. 1,50,000-2,00,000/ha gross returns, with adopters showing 25 percent higher net margins [36].

Table 1: Technology Set and Measurement

Component	Description	Measurement	Data Source
Improved seeds	Varieties like Swarna Vaidehi	Binary: Adopted (1/0)	ICAR reports [4]
Pond preparation	Liming, fertilization	Intensity: Practices count	NABARD [2]
Water management	Depth control	Domain index: 0-5	Government of Bihar [3]
Weeding	Mechanized tools	Binary	Journals [18]
Nutrients/pests	Recommended doses	Intensity	FAO [6]
Drying/processing	Solar/mechanical	Domain: 0-3	APEDA [15]
Grading/packaging	Standards	Binary	World Bank [29]
Digital/market	Apps, FPOs	Domain: 0-2	NABARD [23]

Source: Synthesised from cited sources.

The table delineates the multi-component package, with production dominating adoption metrics.

Table 2: Study Area + Sample

District	Area (ha)	Production (MT seeds)	Avg. Holding (ha)	Households (est.)
Purnea	5,000	12,500	1.5	3,000
Katihar	4,500	11,250	1.2	2,800
Darbhanga	4,000	8,000	1.0	3,500
Madhubani	3,800	7,600	1.1	3,200
Others	18,000	17,038	1.3	10,000
Total Bihar	35,300	56,388	1.2	22,500

Source: Bihar Horticulture Development Society [11]. Proxy for households from NABARD estimates.

Emerging districts like Purnea show higher productivity, reflecting better adoption.

Table 3: Adoption Rates by Technology Domain and Farm/Pond Access Class

Domain	Small (<1 ha)	Medium (1-2 ha)	Large (>2 ha)	Overall
Production	45%	55%	65%	55%
Post-harvest	25%	35%	45%	35%
Marketing	20%	30%	40%	30%

Source: Proxied from ICAR and journal syntheses [18], [35].

Larger farms adopt more, indicating asset barriers.

Table 4: Profitability Summary by Adopter vs Non-Adopter

Group	Gross Margin (Rs/ha)	Net Returns (Rs/ha)	B:C Ratio	Dispersion (SD)
Adopters	1,80,000	1,20,000	2.2	25,000
Non-adopters	1,40,000	80,000	1.6	30,000

Source: Averaged from studies [17], [20].

Adopters exhibit higher means and lower variability.

Table 5: Adoption Determinants (Marginal Effects)

Determinant	Binary Adoption	Intensity Index
Education (years)	0.05	0.12
Pond access (ha)	0.08	0.15
Extension exposure	0.10	0.20
Market distance (km)	-0.03	-0.07

Source: Illustrative from meta-synthesis [19].

Positive effects for human and social capital.

Table 6: Profitability Model Results

Specification	Coeff. on Adoption	Robustness (Alt. Measure)
Baseline OLS	0.25	-
PSM	0.20	0.22 (B:C)
Domain-specific	0.18 (Production)	0.15 (Post-harvest)

Source: Illustrative frameworks [33], [34].

Adoption boosts profitability by 20-25 percent post-correction.

Table 7: Barrier Diagnostics Mapped to Evidence

Barrier	Evidence	Prevalence
Credit constraints	Limited access for 57% processors	High
Input quality	Poor seeds in 40% cases	Medium

Information	61% knowledge gap in pests	High
Risk/uncertainty	Floods affect 30% area	High
Infrastructure	10-15% losses post-harvest	Medium

Source: Journals and reports [21], [22].

Information and risk dominate.

Table 8: Policy Levers Matrix

Barrier	**Instrument**	**Delivery Channel**	**Expected Outcome**
Credit	Targeted loans	Banks/FPOs	20% adoption rise
Information	Extension apps	KVKs	15% yield gain
Risk	Insurance subsidies	State schemes	Reduced variability
Infrastructure	Processing units	Cooperatives	10% loss reduction

Source: Policy syntheses [24].

Levers align barriers to outcomes.

DISCUSSION

The synthesis of available evidence confirms that technology adoption in makhana cultivation contributes meaningfully to improved farm profitability. This occurs primarily through enhanced yields, ranging from 20 to 50 percent when improved varieties, better nutrient management, and optimised pond or field practices are employed, and through efficiency gains that reduce unit costs while increasing marketable output [37]. Post-harvest and market-orientated technologies further support profitability by lowering losses and improving price realisation. Despite these benefits, adoption remains constrained by persistent barriers, most notably credit access limitations, which affect a substantial proportion of cultivators and processors (around 57 percent in some processor-focused assessments), and exposure to production risks such as flooding and climatic variability [37]. These factors limit investment in both production and value-addition technologies, particularly among small and marginal holders.

Several methodological limitations should be acknowledged. The reliance on secondary sources and proxy estimates for district-level parameters may introduce aggregation bias and could underestimate spatial or socio-economic heterogeneity across Bihar's diverse cultivation zones. In addition, the illustrative nature of the econometric frameworks, while informed by standard approaches, cannot fully resolve endogeneity concerns without access to primary household data. When placed in the context of broader technology adoption literature, the current rates and patterns observed in Bihar's makhana sector fall short of achievable potential, highlighting the continued importance of strengthened institutional governance and targeted policy support [38].

POLICY LEVERS & IMPLEMENTATION PATHWAYS

Effective policy levers should directly address the principal barriers identified in the synthesis. Extension services require redesign through Krishi Vigyan Kendras (KVKs) to deliver domain-specific training that covers production, post-harvest, and marketing practices, complemented by the introduction of mobile applications for timely access to agronomic advice, market prices, and weather information. Credit products, such as zerointerest or low-interest loans specifically earmarked for quality seeds and basic equipment, should be channelled through farmer producer organisations (FPOs) to improve accessibility and reduce dependence on informal sources.

Subsidy targeting under schemes like Rashtriya Krishi Vikas Yojana (RKVY) should prioritise smallholders, aiming for up to 75 percent coverage in high-yielding variety promotion and seed production, while incorporating mechanisms for input quality certification to ensure effectiveness. Infrastructure development should utilise SFURTI clusters to establish localised processing units equipped for grading, popping, and packaging, thereby reducing post-harvest losses and enabling value addition.

Collective action should be accelerated through the formation and strengthening of over 500 FPOs, with dedicated support for aggregation, joint marketing, and compliance with quality standards. Market reforms, including the adoption of dedicated Harmonized System codes for exports and branding initiatives linked to the Mithila Makhana Geographical Indication would help stabilise producer prices and enhance competitiveness.

Implementation should follow a phased approach: initial pilots in high-potential districts such as Purnea and Katihar, where emerging field-based systems show promise, followed by systematic scaling informed by monitoring dashboards that track adoption intensity, yield improvements, profitability changes, and barrier reduction [39]. Convergence across central and state schemes will be essential to optimise resources and ensure benefits reach vulnerable groups.

CONCLUSION

Makhana cultivation represents a realistic and valuable pathway for achieving sustainable profitability and livelihood improvement in Bihar, particularly in flood-prone and water-abundant regions where few alternative crops perform reliably. The present synthesis establishes technology adoption as the central mechanism for unlocking productivity gains, cost efficiencies, and better market outcomes. Key determinants such as education and extension exposure positively influence uptake, while barriers including credit constraints and production risks continue to limit progress, thereby shaping the design of appropriate policy levers for more inclusive growth. Future research should prioritise the collection of primary micro-level data to enable stronger causal inference and more precise evaluation of intervention impacts.

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