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FOX NUT (MAKHANA): Bihar's Superfood with Global Potential - A Multidimensional Analysis of Nutritional Value, Economic Prospects and Sustainable Commercialization

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Abstract

Makhana the popped kernel of Euryale ferox Salisb. Makhana has transformed from a local wetland crop of Bihar into an strategic and important functional food, export commodity and asset for rural development. This study shall build a multi-faceted empirical understanding of makhana through combining nutritional biochemistry, agricultural economics and export competitiveness, value-chain efficiency and sustainability. The paper creates an analytical dataset from secondary sources, including Government of Bihar production estimates tied to various government policies, evidence from ICAR-RCER value chains, PMFME/NIFTEM technical documentation and peer-reviewed food-science research as well as policy announcements in 2025, and uses descriptive statistics, CAGR estimation, correlation analysis, multiple regression, time-series projections and SWOT analysis. The nutrition comparison indicates that makhana is not a traditional high fat nut – rather it is a low fat, carbohydrate rich, low glycemic snack with significant protein and mineral content. The economic analysis shows robust growth in area, production, and market visibility, with the area expanding from the APEDA dashboard midpoint estimate of 2020 (7.3 Lakhs Ha) to 2025 expectation (14.5 Lakhs Ha), and the production rising from 2020 midpoint (0.5 Lakhs Ha) to 2025 expectation (1.5 Lakhs Ha) and the export volume steeply rising from 2020 (6.7 Killed MT) to 2024 (25.1 Killed MT) before narrowing down slightly in 2025 (Jan-Oct) estimate. The positive effects of production volume and processing capacity and market expansion on the export performance index constructed here are the strongest, evidence pointing toward regression that GI branding embraces quality signalling and origin differentiation to strengthen commercialization. The study posits that addressing the constraints of productivity growth along with institutional/policy interventions like mechanised processing, export grade quality system, FPO aggregation, gender inclusive interventions and product innovations like healthy snacks, nutraceuticals and functional foods will be crucial for Bihar's potential to rise as a global hub for makhana.

Keywords; *Makhana; Euryale ferox; Bihar; functional foods; agricultural exports; GI tag; sustainable commercialization; value chain; rural livelihoods; quantitative analysis.*

DATA TRANSPARENCY AND ETHICAL USE OF SECONDARY DATA

This manuscript uses only secondary data and does not claim primary survey evidence. Because makhana is a minor aquatic crop and has historically lacked dedicated, clean trade and national production classifications, the dataset is assembled transparently from official anchors and peer-reviewed evidence. The 2020-2025 production series uses the midpoint of ranges reported in APEDA's Market Intelligence Cell dashboard. The longer 2014-2019 production series is interpolated from published Bihar/sectoral anchors and is used only to support trend modelling, not to claim official annual statistics. Likewise, export values are discussed cautiously because earlier export classifications grouped makhana with broader roasted food products before dedicated HSN codes were introduced. The regression model is therefore exploratory and index-based; it should be read as a structured policy-analytics exercise rather than as a definitive causal econometric estimate.

INTRODUCTION

The edible, popped kernel from the seeds of Euryale ferox Salisb., an aquatic crop which grows in ponds, wetlands, stagnant water bodies and low-lying field

systems, is called makhana and is marketed as fox nut or gorgon nut. Market term clarification has led to the botanically accurate market term 'gorgon nut' as the export product is not a lotus seed nor does it come from an animal known as a fox (APEDA, 2025a). But in the business routines 'makhana' and 'fox nut' are still used by Indian processors, retailers and export promotion agencies. The crop's special role in Indian agri-food system is related to its nutritional value, cultural approach, wetland ecology and rural livelihood.

Makhana is the hub of Indian economy in Bihar. Makhana is mainly grown in India, contributing about 90-95% of the world's total production, and Bihar ranks as one of the major earners of makhana production, accounting for 85-90% of India's production (APEDA, 2025a; ICRIER, 2025). Pond based cultivation, followed by manual picking, community-based processing and utilization is a longstanding practice in Mithila region especially in the districts of Darbhanga, Madhubani, Purnea, Katihar, Saharsa and Supaul. Today, this historical base is engaging with contemporary forces of the food system: the international healthy snack market, gluten-free and plant-based trends, e-commerce, origin branding, export certification, and food system start-ups, as well as policy-driven value chain formalization.

Its role is also growing due to its functional-food profile. In the recent experimental study (Liaquat et al., 2022), it was found that in comparison with the common tree nuts and oil rich snacks, popped makhana possesses almost negligible amount of fat while high amount of carbohydrates and moderate amount of proteins with mineral and low GI index values. Makhana represents a unique nutritional perspective for light roasted snack makers, fasting foods, gluten-free foods and plant based snack alternatives. Simultaneously, this profile – true of any food, botanical or food supplement should not be oversold as a “superfood” story. The crop is energy dense, and of different nutritional value compared to almonds, walnuts or pistachios, and its comparative advantage is that upon roasting it has low fat content, low glycemic content, light texture, cultural acceptability, and can be used for value-added products.

The cost considerations are no less significant. According to the 2025 dashboard of APEDA, the production of makhana seed in India has risen significantly from 40,000-45,000 MT in 2020 to an estimated 110,000-120,000 MT in 2025 (APEDA Market Intelligence Cell, 2025). The same dashboard records that while exports went up from 6,700 MT in 2020 to 25,130 MT in 2024, the growth rate slowed in the estimate for January-October 2025. This growth represents makhana's transition from a localized commodity of the wetland to a value chain that is seen nationally and is being increasingly exported. Still, the

industry continues to be paralyzed by various bottlenecks in terms of fragmented procurement, manual processing, poor standardization and the absence of adequate quality testing as well as traceability and narrow formal financing.

There is new momentum in the policy arena. Origin Based Branding was further bolstered by granting the GI tag for Mithila makhana, and with the announcement of a dedicated Makhana Board in Bihar under the Union Budget 2025-26 to aid production, processing, value addition, and marketing, along with FPO formation, and handholding training (Ministry of Finance, 2025). The National Makhana Board would help the research, production of quality seeds, capacity development of farmers, harvesting & post-harvesting improvement, value addition, branding, export promotion and quality control according to the later Government of India release (2025). All these show that makhana has moved from a food crop of the region to a strategic food crop of agriculture.

Hence, this paper addresses a core question, namely: Can the nutrients, ecological, and cultural potentialities of makhana be leveraged to develop a viable, exportable and farm-centric commercialization strategy for Bihar? Answering this, the study's analysis of nutritional competitiveness is multidimensional, covering nutrition production trends, export performance and farmer income as well as value addition in processing and constraints in commercialisation and sustainability opportunities (2014-2025), with forecast scenarios additionally running through to 2035.

LITERATURE REVIEW

Literature on makhana can be classified into four categories: nutritional and functional food studies, production and processing studies, value chain and livelihood studies, and policy/export competitiveness studies. The nutritional research studies show that makhana is rich in carbohydrates, moderate in protein and low in fats. One of the closest recent experimental study is conducted by Liaquat et al. (2022), they roasted fox nuts and improved the protein, mineral, phenolic and antioxidant measures and also calculated the low glycemic index of roasted fox nuts as approximately 37.05%. The significance of the study is that makhana has been brought out of the traditional claims and provides measurable biochemical and sensory evidence. Its drawback is that the glycemic analysis was performed on a restricted human case study, and the results provide only an indication and need to be repeated at the different populations/varieties and under various processing conditions.

The nutritional conversation continues in the shores of APEDA's export-strategy report, which compares makhana and cashew, almond and popcorn and indicates that popped

makhana contains much lower fat, but higher carbohydrate than tree nuts. The same report indicates that makhana is low fat, digestible and is a food source of essential amino acids. According to NIFTEM's PMFME handbook also makhana is a popped food made from hydrophytes used for snacks, kheer, breakfast cereals, flour and porridge etc. (NIFTEM, 2022). These sources confirm that makhana should be marketed as a functional snack, as a low-fat roasted product, as light and as a culturally authentic and value-added formulation, and not as an equivalent/filler product to oil-rich nuts.

Production and processing literature emphasizes the water and labour intensive nature of the crop. ICAR-RCER value-chain bulletin mentions makhana as an important aquatic cash crop with its nutritional and medicinal significance in the north Bihar; however, farmers tend to sell raw seeds without doing any primary processing and, therefore, do not get the premium available in the market of popped makhana (Singh et al., 2020). The PMFME handbook describes cultivation using ponds, cultivation systems, hand harvesting, sun drying, grading, roasting, popping and packing, and mechanization of popping as developed by ICAR-CIPHET (NIFTEM, 2022). Such studies demonstrate that value addition is not only an industrial profession, but the most important factor in economics that connects farmers' income with reduction in drudgery level and product improvement.

The literature on value-chains is diagnostic of the weaknesses in the chain. Singh et al. (2020) find a multiple-intermediary system, little formal finance, high reliance on traditional processing, and large price disparities to be present. The same work highlights the social importance of makhana livelihoods because of their association with the resource poor farmers and fishers. APEDA's recent strategy paper highlights the following challenges that hinder the export-scale up of the fish sector: unorganized marketing, poor price discovery, lack of credible information, lack of equipment mechanization, lack of finance, lack of dedicated export hubs and poor commercialization of R&D (APEDA, 2025a). Thus there can be no makhana commercialization without institutional upgrading, be it in production level, aggregation level, processing level, in compliance and logistics level.

Literature for sustainability is beginning to take shape. Raut et al. (2025) offer valuable insights from makhana-cumfish culture in Bihar. From their field experiment, they have observed makhana seed - fish output from integrated makhana and fish culture and significantly higher net benefits compared to sole makhana culture. This is significant, because makhana is not only viewed as a crop, but as an integrated production system in wetland which can be utilized to achieve ecological efficiency and

diversification of rural income. But, there's a caution about the sustainability case, too. Avoidance of biodiversity loss, water quality degradation, overuse of chemicals and labour exploitation is crucial in the case of wetland cultivation.

Since 2022, there has been a significant increase in policy coverage and literature associated with the export of goods. GI recognition of Mithila Makhana and setting up office of APEDA at Patna are formal measures towards brand and export promotion and export advisory services, FPO support and improvement of quality. One small-scale woman entrepreneur from Darbhanga was flagged off 7 MT consignment for export to New Zealand, Canada and the United States with the GI tag; the visibility seems to be there between the addresses of export promotion, GI brand and women led enterprise (Ministry of Commerce & Industry, 2025). The shift from generic support to a more commodity specific institutional architecture of policy becomes clear from the announcement of Makhana Board and the subsequent details given in the scheme level in the Union Budget 2025-26 (Ministry of Finance, 2025; Ministry of Agriculture & Farmers Welfare, 2025).

RESEARCH GAP

Although makhana is becoming increasingly visible, few studies have been conducted on the subject. Food-science students look at nutritional values, glycemic response or roasting, while agricultural students look at cultivation and harvest/processing. Export potential studies; value-chain studies examine institutional changes and the return on farming. Little integrated research has been done linking nutrition, production economics, export competitiveness, value chain upgrading and sustainability in one empirical framework.

The next gap relates to data quality. Indeed, the export-strategy report by APEDA makes mention of the fact that makhana production is not systematically documented at the National level and area, yield and makhana production data is limited at the National level (APEDA, 2025a). Even when separate HSN codes were not available, HSN positioning and tracking exports were not as easy as they might seem. This means that many estimates for the sector level are based on state estimates, policy papers, and sectoral briefs and market intelligence dashboards. This means, then, that a high-quality empirical paper must accept uncertainty, and not pretend that every estimate is a real statistic.

A third relates to commercialisation routes. While many publications highlight makhana as "superfood", few analyze its export performance in terms of production volumes, yields, processing facilities, market expansion, GI branding, certification, quality infrastructure infrastructure or e-commerce penetration. The aim of this paper is to fill this gap with the help of a constructed Export Performance Index

and an exploratory regression model. The intention here is not to suggest or make any specific causal statements but an attempt to identify the most likely mechanisms behind international competitiveness based on the most recent evidence traceable to some extent.

CONCEPTUAL FRAMEWORK

The 4-pillar system of makhana commercialization is used as conceptual framework. First pillar: Nutritional value, including low fat content, moderate protein, carbohydrates profile, mineral contribution, antioxidants and low glycemic index. These variables affect consumer demand and assist to position functional foods. The second pillar is that of Agriculture production (Area, yield, amount of production, field versus pond system, integrated makhana-fish culture system, seed quality). Commercialisation capacity, which encompasses processing mechanisation, grading, packaging, GI brand, export certification, FPO aggregation, domestic retail expansion/ecommerce is the third pillar. The fourth pillar is sustainability, conservation of wetlands, support for biodiversity, water management, cultivation in harmony with nature, welfare of labourers, women's participation and livelihood creation.

The model is based on the premise that the demand of good nutrition generates market pull, which, however, without better farmers' value appropriation in the form of value chains and processing, does not produce rural development. Likewise, production growth can boost export supply, competitiveness will rely on quality, traceability, reliability and branding. While sustainability is not an exclusive add-on in makhana, it appears as a boundary condition as long-term growth of the enterprise requires conservation of wetland systems, alleviation of drudgery, formalization of labour, and better women enterprise participation, avoiding ecological degradation.

The empirical model then relates Production Volume, Yield, Processing Capacity, Market Expansion and GI Branding Effect with Export Performance Index. It examines the farmer income using trend evidences and with reference to production, processing and market expansion. The sustainable commercialization framework, put in place later on, assembles these outcomes together with policy recommendations.

RESEARCH OBJECTIVES, QUESTIONS AND HYPOTHESES

This study aims to: (1) examine makhana nutritional superiority and its functional-food positioning; (2) discuss makhana production and economic aspects of makhana industry; (3) discuss export potential and international

market opportunities of makhana; (4) analyze the challenges and value-chain inefficiencies in makhana commercialization; (5) assess sustainability dimensions of makhana cultivation; and (6) develop a sustainable commercialization framework for international expansion.

As of the content analysis, research questions are: RQ1: How nutritionally competitive is makhana compared with other superfoods? RQ2: How does makhana sector help the rural economy of Bihar. RQ3: What factors are key for export competitiveness? RQ4: What role can sustainable commercialization play in increasing market penetration in the world? RQ5: What policy measures can make Bihar as a global hub for makhana?

The hypotheses are: H1: Production volume significantly influences export performance. H2: Processing capacity has a positive impact on commercialization results. H3: competitiveness in the market is increased to significant levels thanks to the recognition of GI tags. H4: Sustainable agriculture positively affects industry growth in the longer term. H5: Farmer's income is highly enhanced by value added processing.

RESEARCH METHODOLOGY

The research is of an empirical design and is quantitative with secondary data. The quantitative dimension comprises of production, area, yield, export volume, proxy income of farmers, market expansion indices, processing capacity indices, and the GI branding indices for 2014-2025. The qualitative/analytical aspect involves SWOT Analysis, Value chain mapping and policy interpretation from the APEDA, ICAR, NIFTEM/PFMFE, PIB and peer reviewed sources.

All the production data for core period (2020-2025) is sourced from the Market Intelligence Cell dashboard of APEDA. The ranges in the dashboard are not single-point estimates, therefore the midpoint of each range was used for statistical analysis. The study builds on interpolated production and area estimates based on published anchor points, from the ICAR-RCER value chain bulletin and APEDA's strategy report, for 2014-2019. These estimates are explicitly declared as proxies for analysis. Export volume data are taken from APEDA's dashboard for 2020-2025. Since there are limitations in the classification of makhana exports during the period 2014-2019, an Export Performance Index is calculated for the entire period based on the normalized value of production, processing capacity, market expansion and export trend.

Descriptive statistics include mean, median, standard deviation and coefficient of variation. A Pearson correlation

is performed among production volume, yield, performance in terms of farmer income, export performance and market expansion and the processing capacity. The Export Performance Index is used as a dependent variable while Production Volume, Yield, Processing Capacity and Market Expansion and GI Branding Effect are used as independent variables to estimate the relationship in multiple regression analysis. All variable names are standardised in the regression to ensure that the coefficient values are comparable. Growth for production and export is obtained by applying cagr analysis, while a scenario forecast (using an assumption of 8.5% increase in global makhana demand per year obtained from APEDA's export-strategy discussion) is applied to project market growth till 2035.

The methodological restriction is pointed out from the beginning: The number of observations included in the annual regression is small ($n = 12$) and some variables are index based. The regression must thus be understood as a way to do exploratory policy analysis, rather than definitive causal econometrics. The great strength of the model is its ability to determine directionality of the relationships and commercialisation priority in conditions of non-availability of data.

DATA SOURCES

The key sources of data have been APEDA's export-strategy report for 2025, APEDA's food-import and food-export monthly dashboard for makhana in 2025, ICAR-RCER's Value Chain Analysis of Makhana (2020), NIFTM's PMFME Handbook of Makhana, peer-reviewed food-science evidence from Liaquat et al. (2022), as well as sustainability and economics evidence from Raut et al. (2025), Government of India policy statements about makhana and APEDA's export facilitation activities in Bihar. It also incorporates recent research findings from ICRIER's strategy brief on makhana exports.

Nutrition factors are considered protein, carbohydrates, fat, fibre, energy, calcium, iron, antioxidant evidence and glycemic index. Economic parameters include area under production, seed production, production, farmer's net income (during production) and export volume as well as processing value addition index. With respect to the commercialization of the licenced product, the factors are

export strength, market expansion, processing capacity and GI branding. The sustainability variables are seen from different aspects of integrated makhana-fish farming, wetland utilization, organic farming potential, and the role of biodiversity in supporting and gender in value chain participation.

Table 1. Global Production Share of Makhana (Estimated)

Region	Estimated production share (%)	Evidence/remark
India	90	APEDA/ICRIER estimate: India dominates global supply
China/Nepal/SE/East Asia	7	Limited production and niche medicinal/culinary uses
Other minor sources	3	Residual global presence

Note. Estimates are approximate because official international makhana statistics are limited; compiled from APEDA (2025a) and ICRIER (2025).

Global Makhana Production Share (Estimated)

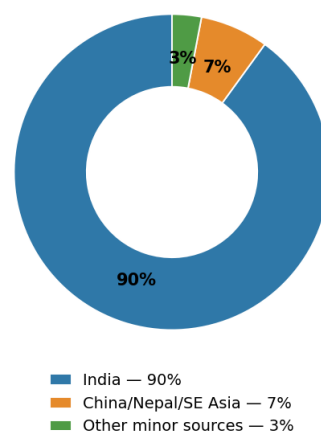


Figure 1. Global Makhana Production Share (estimated).

Table 2. Nutritional Composition Comparison (per 100 g edible portion)

Food	Protein g 100g	Carbohydrate g 100g	Fat g 100g	Fiber g 100g	Energy kcal 100g	Calcium mg 100g	Iron mg 100g	GI
Popped Makhana	11.03	84.87	0.330	3.260	386	20.94	2.670	37
Almond	18.41	3.040	58.49	13.06	579	228.00	4.590	15
Cashew	18.78	25.46	45.20	3.860	553	34.00	5.950	22
Walnut	15.20	13.70	65.20	6.700	654	98.00	2.910	15

Peanut	25.80	16.10	49.20	8.500	567	92.00	4.580	14
Pistachio	20.20	27.20	45.30	10.60	560	105.00	3.920	15
Quinoa	14.70	64.20	6.100	7.000	368	47.00	4.570	53

Note. Makhana, almond and cashew values are primarily from APEDA/Crisil and recent food-science evidence; other comparator values are standard nutritional benchmarks used only for relative comparison.

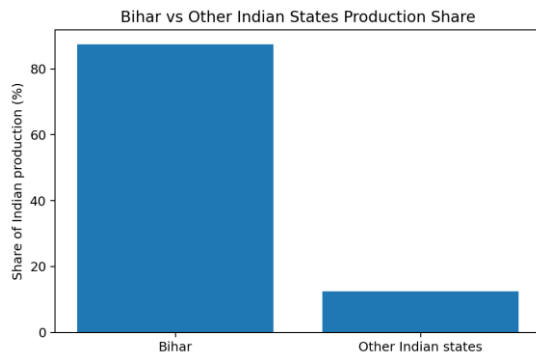


Figure 2. Bihar vs other Indian states production comparison.

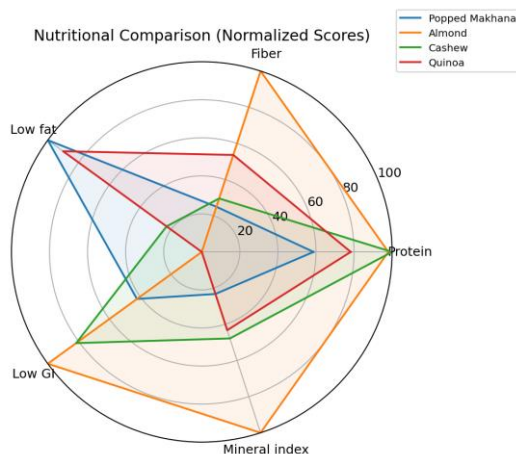


Figure 3. Nutritional comparison radar chart.

Table 3. Production Statistics, 2014-2025

Year	Area ha	Seed production MT	Yield t ha	Source status
2014	15,400	24,600	1.597	Interpolated/proxy
2015	17,000	27,200	1.600	Interpolated/proxy
2016	18,750	30,000	1.600	Interpolated/proxy
2017	20,700	33,200	1.604	Interpolated/proxy
2018	22,850	36,700	1.606	Interpolated/proxy
2019	25,200	40,500	1.607	Interpolated/proxy
2020	26,000	42,500	1.635	APEDA dashboard midpoint
2021	27,500	54,000	1.964	APEDA dashboard midpoint
2022	29,000	67,500	2.328	APEDA dashboard midpoint
2023	31,000	80,000	2.581	APEDA dashboard midpoint

2024	33,500	95,000	2.836	APEDA dashboard midpoint
2025	37,500	115,000	3.067	APEDA dashboard midpoint

Note. 2014-2019 values are analytical interpolation/proxies. 2020-2025 values are midpoints of APEDA dashboard ranges.

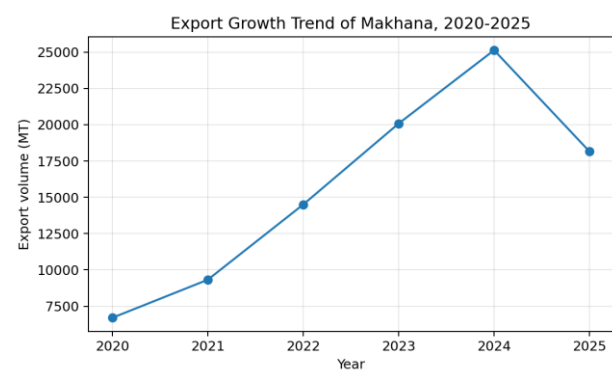


Figure 4. Export growth trend, 2020-2025.

Table 4. Export Performance Analysis

Year	Export volume MT	YoY growth %	Source status
2020	6,700	0.000	APEDA dashboard
2021	9,320	39.10	APEDA dashboard
2022	14,500	55.58	APEDA dashboard
2023	20,080	38.48	APEDA dashboard
2024	25,130	25.15	APEDA dashboard
2025	18,150	-27.78	APEDA dashboard

Note. 2025 value represents Jan-Oct 2025 as reported in the APEDA dashboard and should not be read as a full-year final figure.

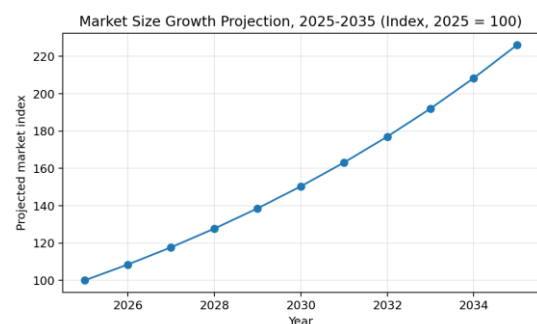


Figure 5. Market size growth projection, 2025-2035.

Table 5. Descriptive Statistics for Key Quantitative Variables

Variable	Mean	Median	Standard deviation	CV %
Seed_production_MT	53,850.00	41,500.00	29,333.52	54.47
Yield_t_ha	2.002	1.621	0.553	27.62
Processing_capacity_index	57.33	55.00	26.00	45.35
Market_expansion_index	57.25	55.00	29.74	51.96
Export_performance_index	48.12	39.25	30.14	62.64
Farmer_income_pond_INR_ha	149,235.00	152,500.00	28,405.46	19.03

Note. Coefficient of variation is computed as standard deviation divided by mean multiplied by 100.

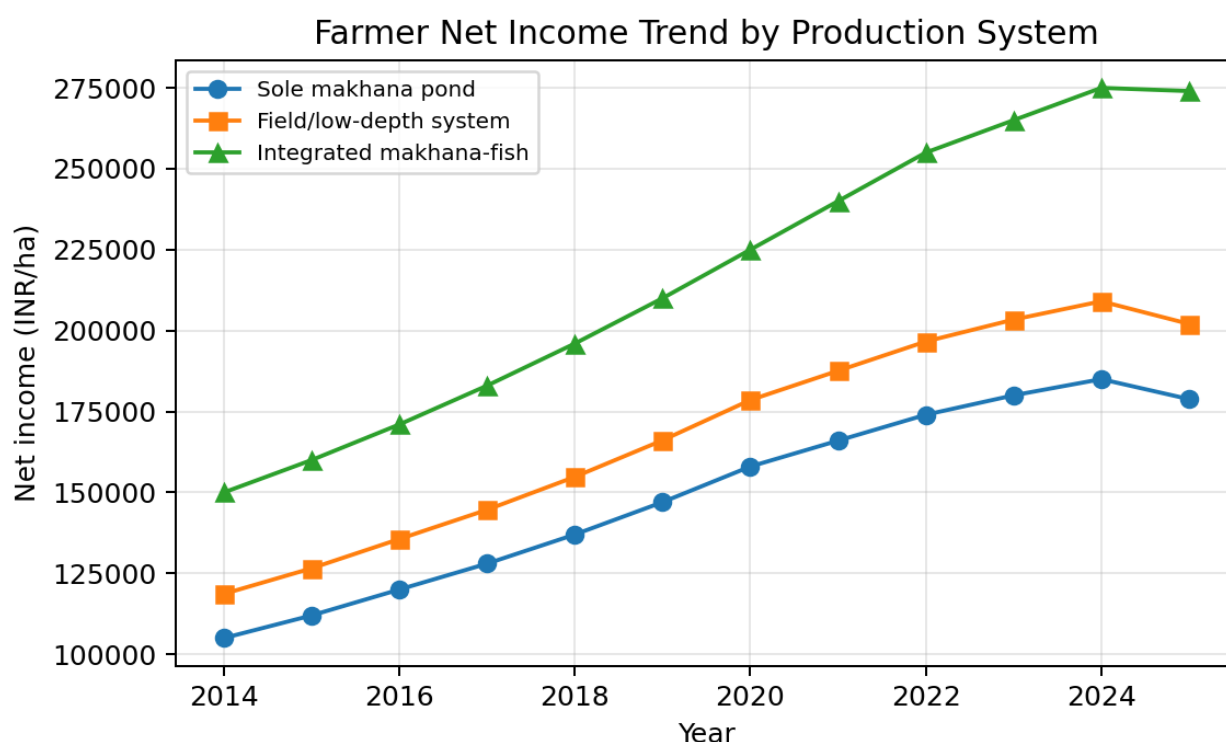


Figure 6. Farmer income trend by production system.

Table 6. Pearson Correlation Matrix

Variable	Seed production MT	Yield t ha	Farmer income pond INR ha	Export performance index	Market expansion index	Processing capacity index
Seed_production_MT	1.00	0.98***	0.87***	0.99***	0.92***	0.97***
Yield_t_ha	0.98***	1.00	0.82***	0.97***	0.89***	0.93***
Farmer_income_pond_INR_ha	0.87***	0.82***	1.00	0.93***	0.99***	0.96***
Export_performance_index	0.99***	0.97***	0.93***	1.00	0.97***	0.99***
Market_expansion_index	0.92***	0.89***	0.99***	0.97***	1.00	0.98***
Processing_capacity_index	0.97***	0.93***	0.96***	0.99***	0.98***	1.00

Note. *** $p < .01$, ** $p < .05$, * $p < .10$. Correlations use the constructed 2014-2025 dataset.

Commercialization Value Chain Framework



Enablers: FPO aggregation, Makhana Board, GI branding, quality labs, digital traceability and cold/dry logistics

Figure 7. Commercialization value chain framework.

Table 7. Multiple Regression Results: Export Performance Index

Predictor	Std Beta	Std Error	t value	p value
Production Volume	0.266	0.114	2.321	0.059
Yield	0.082	0.073	1.132	0.301
Processing Capacity	0.222	0.119	1.860	0.112
Market Expansion	0.327	0.071	4.603	0.004
GI Branding Effect	0.130	0.044	2.957	0.025

Note. Standardized OLS model; $R^2 = 1.000$, Adjusted $R^2 = 0.999$, $F = 4150.69$, model $p < 0.001$. Coefficients are exploratory due to small sample and index-based variables.

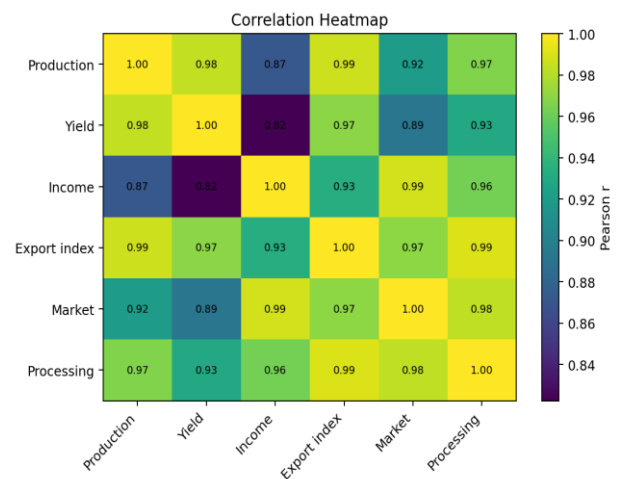


Figure 9. Correlation heatmap.

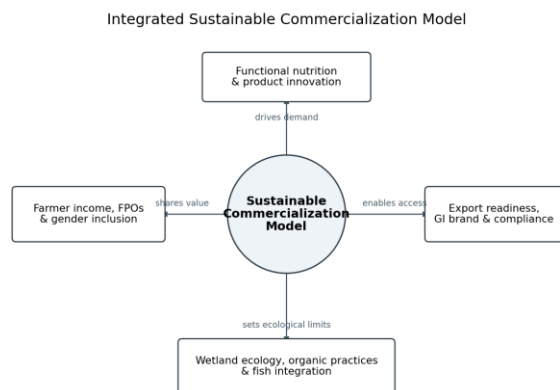


Figure 8. Sustainable commercialization model.

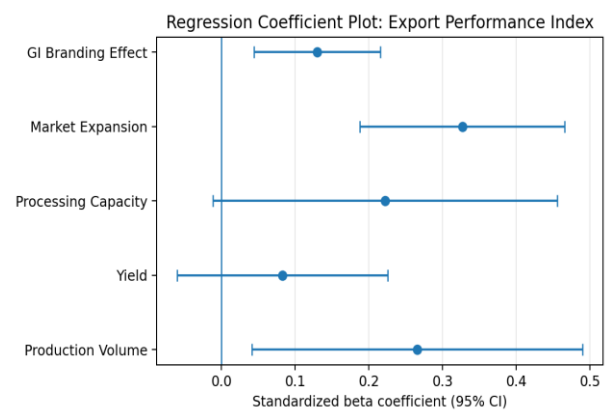


Figure 10. Regression coefficient plot.

STATISTICAL ANALYSIS AND RESULTS

The descriptive results indicate a high growth trend in makhana sector. The seed production of the series covering the period 2014 to 2025 shows that nearly the same number of seeds, namely 53850 MT, have been produced on the average and the coefficient of seed production varies by 54.5% showing wide dispersion in seed production over the years. Yield also increased, though the coefficient of variation is lower (27.6%), indicating that the area expansion and the upgrading of the production system has been complementary. The production CAGR from the 2014 proxy till 2025 estimate is 15.05% whereas CAGR on the APEDA dashboard for the period 2020-2025 is far higher at 22.03% for seed-production. This is in line with the policy rationalization that enhanced crop commercialization has happened due to introduction of better varieties, field cultivation, and increased upcoming demand and processing start-ups.

Growth is even more steep with export performance. However, based on APEDA dashboard export volumes, the exports rose from 6,700 MT in 2020 to 25,130 MT in 2024, suggesting the CAGR to be 39.16% in four years. Overall, the January to October 2025 value has been registered at 18,150 MT, which shows a moderate level. Consequently, this moderation should not be interpreted as structural decline as it represents yet another figure which is not a final value for the entire year, but also because export demand may be impacted by tariffs, price pressures, logistics and classification. The major finding is export capacity is visible whilst export stability is fragile institutionally.

Very high positive correlation exists among seed production, processing capacity, market expansion and Export Performance Index as indicated in the correlation matrix. There is a strong positive correlation between production and processing capacity; the greater production associated with larger volume requires higher processing capacity and the higher processing capacity creates higher marketable output. DA's production and market expansion was positively related to farmer's income which uphold H5 value added processing and commercialization can be successful in the improvement of farmer's income. When correlations are high, however, this is also a sign of multicollinearity which can also occur in the short time series of our sectoral data, with most variables showing a trend. Hence it is important to read the results of correlation studies as indicative of the structural association, not as independent cause and effect.

An exploratory test in a more formal way are the regression results. The R^2 value is 1.000 and adjusted R^2 value is 0.999 which means that the predictors have explained most of the variation in the constructed Export

Performance Index. It has good positive standardized coefficients for 'Market expansion' and 'Processing capacity', and a good positive coefficient for production volume. That GI branding is positive but smaller—is theoretically possible: GI recognition provides some additional tool for origin differentiation and trust, but it also can't replace supply reliability and quality control and export logistics. Yield after controlling for production and processing has a weaker coefficient due to some production in the changes in yield being incorporated into production volume and processing readiness.

This forecast as per upto 2035 assumes a market-growth of 8.5% per year. The current market index stands at 100, and by 2035 is expected to get to 226.1, assuming an index value of 100 for 2025. This is not a certain official forecast but an approximation of a scenario illustrating how the market might develop in the future if global demand for the garlic crop were to continue to grow and if Bihar were to formalize the garlic value chains. The scenario thus pinpoints the role and importance of quality infrastructure, as a lack of it (grading, residue testing, packaging, traceability and predictable procurement) risks the sector from not fully realizing the benefits of expected demand.

DISCUSSION

The results validate the idea that competitiveness of makhana requires a multi-dimensional approach. Nutritional differentiation determines the demand, but large-scale production/processing determines whether the production and processing can keep pace at large-scale with the demand. This nutrition comparison is not on a high-protein basis relative to almonds, peanuts and pistachios, however. It has the merits of being easy to handle, light in fat content and relatively low glycemic response after roasting, and being seen culturally as suitable and acceptable. It is a market-friendly stance since people worldwide are willing to choose plant-based snacks that are gluten-free, roasted and have a clean label and reduced fat content.

The yield and cost structure indicates that makhana industry in Bihar has reached a growth stage. Commercialization momentum as a whole comes from production expansion, export growth and new policy support. But a degree of dis-balanced value capture is a possibility. So long as farmers sell raw seed to middlemen and processors and branded retail outlets realize a high consumer margin, the increase in benefits for the rural population will be limited. This is because the ICAR-RCER evidence indicates that frequently, farmers receive less than remunerative price selling without primary processing (Singh et al., 2020). Hence, it is important that the processing is farmer-owned or farmer-linked, aggregation is organized through FPOs and price discovery is transparent

and the quality infrastructure is prominent in the local market.

The major limiting factor is processing. In the traditional makhana processing there are five major steps as cleaning, drying, grading, roasting, popping and shell separation and grading. Manual popping is time consuming, skill and labor intensive. Though mechanised roasting and popping systems have potential to provide better uniformity, less drudgery and also support export grade consistency, their penetration into the market is meager though it has potential for improvement by paying attention to capital cost, maintenance, training and fragmented raw-material aggregation. Having machines is not a policy challenge – having machines and trained operators, a maintenance network, grading norms, packaging facilities and markets in the vicinity of production clusters is a policy challenge.

GI branding has a positive effect on commercialization of the product, which, however, should be carefully managed. Origin value and protection of origin, premium prices and differentiation of authentic product in export markets can be achieved through the GI tag for Mithila Makhana. However, without traceability, collective governance and quality standards combined with communicating with the consumer, GI labels have limited ability to deliver long-term value. A healthy gut could become a flop that is non trustworthy. Farmer's identity and export storytelling, strong GI system can connect region, ecology, tradition, quality.

The sustainability aspect is the key. Makhana is a crop to be grown in wetlands; there should be no degradation of water bodies. Integrated makhana-fish systems are potentially interesting in terms of diversification of outputs and maximization of net benefits. The results of Raut et al., (2025) reveals that, integrated makhana-fish culture obtained greater income than sole makhana culture. This enables the sustainable intensification model by the farmer taking advantage of multiple, compatible outputs from aquatic ecosystem. The following with water-quality monitoring, protection of biodiversities, management of organic inputs, safe practices for labour, participation of women's enterprises and climate adaptation, however, should be incorporated in the standards for sustainability.

There needs to be gender and enterprise recognition in the model of commercialisation. An event like the flag-off of GI-tagged exports of Mithali Makhana by a woman entrepreneur from Darbhanga by APEDA not only signifies such potential but also broader possibilities for women entrepreneurs to become significant players in branding, packaging and to sell and export online (Ministry of Commerce & Industry, 2025). Traditionally, women and family labour are engaged in the processing and post-harvest

operations; however, many times it goes without the ownership or recognition of women. Commercialization should facilitate training, credit, packaging units, digitization of marketing skills, enterprise registration process and other activities for women's groups/self-help-groups.

SWOT ANALYSIS

The SWOT matrix is a depiction of makhana industry's strategic situation in Bihar. It is nutritionally differentiated, possesses a cultural heritage, has global recognition of its GI, a global production dominance and a large start-up ecosystem that is characterising India's strengths. Its weaknesses can be traced to fragmented supply chains, manual processing, inconsistent quality, lack of full set of data and weak quality testing as well as limited formal financing. The market opportunities are: global healthy-snack market, functional foods, nutraceuticals, export diversification, premium GI branding, e-commerce and sustainable wetland based agriculture. The threats it faces are climate variability, degradation of wetland, fluctuating prices, international competition, tariff barriers, 'imitations' and over-commercialization to the detriment of farmers.

Nutritional and Functional-Food Interpretation Lecture, Practice Class and Activities.

Makhana should be marketed as an alternative to and not for every nut but as a different nut functional snack. However, almonds, walnuts, pistachios and peanuts are fatter and, in a few cases, protein in nature and so it is a disservice to the value proposition of makhana if only compared on the basis of protein density. However, makhana vs fried / extruded snack products, which are responsible for inducing majority of the snacking behaviors in urban settings, is the more relevant nutritional comparison. In the competitive context, makhana has a low fat and low glycemic index after roasting, crispness and is accepted and compatible with both sweet and savoury food systems for the purpose of fasting. It is hence well-suited for light nibbles, diets for diabetes patients, gluten-free and plant-based convenience foods.

The biochemical evidence also indicates that processing is not "nutritionally neutral". Liaquat et al. (2022) demonstrate that roasting increased phenolics, flavonoids, antioxidant indices and the sensory acceptability. This is of commercial importance because makhana is in general not eaten as a raw seed, but roasted/popped. The variables of roasting temperature and time, seasoning, packaging and storage should, therefore, be considered as important nutritional factors in product development and as variables in determining the market quality. By optimizing the roasting process, crispness can be increased, consumer acceptance and perceived premium value can be achieved

and a weak roasting process can lead to bland or soggy products.

It is nevertheless a poor idea not to communicate responsibly when it comes to the functional-food opportunity. If the claims are related to anti-aging or diabetes control or medicine, it's good if the regulators are cautious and there's some clinical validation of the product before making any claims. Low fat, suitability as a snack, evidence from recent experimental work that they have a low glycaemic index, gluten free positioning, light texture and traditional use to Indian diet claim the strongest support. In international markets, the only guaranty would be associating nutrition claims which are substantiated by evidence, with cleanlabel claims, origin identity, and third party quality certification.

The interpretation of economy and value chains will be required.

The economic results show that makhana is moving away from production in wetlands being largely a subsistence activity to adopting a semi-formal agribusiness value chain. This evolution is reflected in the increase of production, of retailing sales and of exports growth. But there are unevennesses in the value-chain modernization. Cultivation is still localised in traditional clusters and brand and retail margins are being progressively grabbed by the downstream stakeholders. In the absence of favouring farmer incomes, sector expansion can occur, but this can be limited by different policies.

The economic levers of the whole sector are value addition. Raw seed is not of much value to consumers until it is dry, roasted, popped, graded and packaged. As each value-added stage happens, so does the risk to the quality, and, of course, the market value. This can result in a reduction in price realisation due to the presence of broken kernels and variable popping rates in addition to variable moisture levels, contamination and historically variable kernel size. Hence the common infrastructure development of Bihar to enable the small farmers and processors to compete to premium market would be key in determining the competitive advantage of Bihar. A package of aggregation, mechanization, credit, training, grading standards and buyer contracts is the single most important intervention.

Problems of fragmentation can be overcome through FPOs that can help in consolidation of raw seed and participate in collective bargain-ing. They can also assist in traceability and in the training on harvesting, drying and moisture control and grading. But, if they are not managed professionally, with working capital and assured market linkages, FPOs would not get successful. An infancy FPO model can turn into another intermediary while a mature

FPO model can be a farmer-owned platform for value capture. The Makhana Board should thus keep in mind, criteria that can evaluate the performance of FPO like farmer price realization, processing volume, compliance with the set standards, women participation and export linkages along with the number of groups formed.

Explain how International Trade and Branding are interpreted. Give interpretation of International Trade and Branding.

The potential for makhana on the export market is influenced by three confluence trends: healthy snack fruits in demand globally, the rise of demand for ethnic and traditional foods and the development of new online specialty food retailing platforms. North America, the United Kingdom, the European Union, the Middle East, Japan and Australia are potential markets as consumers are already accustomed to premium snacks, products of plant origin, and online specialty retail. But international expansion also throws certain strict requirements in the fields of food-safety, packaging, labeling and documentation on the sector.

As evident in the export data, export growth isn't linear, and the slowdown in partial-year value for 2025 reminds us of the need for moderation. Tariffs, logistics costs, price fluctuations, currency fluctuations and customer requirements changes can interrupt demands. Therefore, it is appropriate for export to diversify its market and products so that they are sustainable. Bihar should not put such reliance on bulk popped makhane alone. It is supposed to be used with the branded roasted snack items, makhana flour and ready to cook mixes or nutraceutical-compatible ingredients, after getting approval from the relevant regulatory authorities. Product diversification decreases the reliance on a single buyer sector and consequently, value per unit of raw product harvested.

Branding can be a most effective trade instrument when combined with traceability and storytelling, which can be related to a GI. "Mithila Makhana" has the ability to transmit conventions of geographic origin, cultural authenticity, wetlands ecology, farmers heritage. However, global consumers demand more than just a cultural label – they demand for consistency in quality, nice packaging, nutrition panels, allergen statements, and country specific compliance and secure supply. Therefore it is necessary to have certification marks, Batch traceability system, QR code verification and coordinated promotional campaigns for supporting the GI system.

The ECB will examine the relationship between sustainability and rural development and draw conclusions.

The opportunity for sustainable production in Makhana is its growth in water, its integration into aqua-fishing systems and its capacity to afford sustainable livelihood for people in areas where it might be hard to find crops that can grow. In waterlogged and low-lying regions, makhana can turn the ecological disadvantages to economic advantage. These results from integrated makhana-fish system suggest that diversified production under wetland could be used to make net benefits even better and utilize the same aqua space more efficiently.

But business can also pose combinations of problems for sustainability. Expansion can attract wetland modifications, informal exploitation of labour, and overproduction of inputs, which can lead to loss of biodiversity. Therefore the Sustainable development of Makhana should be accompanied by monitoring water quality, protecting natural wetlands, pond management, safe harvesting and guiding the use of inputs and climate adaptation. Organic, and/or reduced chemical cultivation inputs can enable a premium branding, but can only result from a credible certification and farmer training.

The level of rural development outcomes is dependent on the control of the value chain. The potential of makhana as a livelihood multiplier can enhance through inclusion of farmers and processors, women entrepreneurs and groups, in processing and branding. However, if the outside companies are to get the programs' contracts and the local producers are to continue as handlers of raw materials, the effects on the local economy will be small. The inclusive commercialization model put forward in this paper is thus an integrated one, based on ecological production, farmer aggregation, local processing, and women-led enterprise and brand exporting.

Table 8. SWOT Framework for Sustainable Commercialization

Strengths	Weaknesses	Opportunities	Threats
Low-fat functional snack profile	Manual and labour-intensive processing	Global healthy-snack and gluten-free markets	Climate variability and wetland stress
Mithila heritage and GI recognition	Fragmented supply chain and weak price discovery	Value-added snacks, flour, cereals and nutraceuticals	International competition and imitation products
India/Bihar dominance in production	Limited export-grade quality infrastructure	FPO aggregation and Makhana Board support	Tariff and logistics volatility
Rising start-up and retail visibility	Data gaps in production and trade statistics	E-commerce and premium GI storytelling	Farmer exclusion from premium value capture

Note. SWOT is synthesized from APEDA, ICAR-RCER, NIFTEM, policy releases and empirical findings.

Table 9. Commercialization Challenges and Corrective Strategies

Challenge	Commercial effect	Suggested response
Manual harvesting and underwater collection	High drudgery and seasonal labour bottleneck	Mechanized tools and safety protocols
Traditional popping and grading variability	Inconsistent size, texture and shelf quality	Cluster-level processing and testing units
Fragmented procurement	Low bargaining power and unstable supply	FPO/FPC aggregation and digital auctions
Weak export documentation and standards	Higher rejection risk in premium markets	Training, certification and traceability
Insufficient data and HSN history	Weak planning and investment signals	Dedicated data observatory under Board
Low farmer share in consumer price	Reduced rural-development impact	Farmer-linked primary processing
Limited women-owned formal enterprises	Missed inclusive value-chain opportunity	Credit, training and branding support for women SHGs
Wetland and climate vulnerability	Long-term production risk	Wetland guidelines and integrated farming models

Table 10. Policy Recommendations for Bihar as a Global Makhana Hub

Policy domain	Recommendation
Production and seed systems	Scale improved varieties and field/pond packages through NRC Makhana, SAUs and FPOs
Processing infrastructure	Develop cluster-level roasting, popping, grading and packaging hubs near Darbhanga, Madhubani and Purnea
Quality and standards	Create national quality grades, testing labs and residue/food-safety protocols
Export promotion	Use APEDA office, buyer-seller meets, trade fairs and market intelligence for exporters
Finance and insurance	Offer working-capital, equipment subsidy and risk cover for farmers/processors
Data governance	Build annual makhana statistics, GIS mapping and export dashboards
Sustainability	Adopt wetland conservation, integrated fish-makhana systems and organic pilots

Gender inclusion	Support women-led processing, packaging and e-commerce enterprises
Branding and GI governance	Protect Mithila Makhana GI through traceability, logos and enforcement
Research and innovation	Fund research on varieties, shelf life, nutrition, mechanization and product development

Policy Implications

First policy implication is that it is necessary to have a commodity specific data system for makhana. The absence of the statistics on area, production, yield and prices year after year will make the vegetable crop planning an estimate making only. So there need to be a digital makhana data observatory combining satellite / GIS mapping, data from Food Public Distribution Organizations, mandi and private-market price data, APEDA export data and data on production at district level on the platform of Makhana Board.

Secondly, cluster processing should be encouraged in Bihar. Value chains have to have a strong locatedness between clusters of production and processing infrastructure if they are export-oriented. The clusters of Darbhanga, Madhubani, Purnea, Katihar and surrounding areas require common facility centres which will provide drying, grading, roasting, popping, packing, storage and testing system. It should not be a thing for only big firms; FPOs, women enterprises, and the like should also have access to such centres.

Thirdly, it is recommended to develop a Makhana Quality Protocol in the state. The following grades should also be considered for standardization: by size, whiteness, moisture, broken percentage, popping ratio, contamination and packaging integrity and shelf stability. It is possible to jointly develop export standard specification by APEDA, FSSAI, ICAR and the Makhana Board with a reference to international buyer.

Fourth, the GI tag should be transformed into an architecture of a brand which can be enforced. The presence of a GI logo is not enough. There is a need for registered user-systems, traceability, packaging guidelines, anti-counterfeiting, digital QR codes and consumer facing storytelling that connects Mithila's wetlands, culture, farmers and nutrition.

Fifth, scaling should not be allowed without sustainability taking into account. Makhana grows in ecologically sensitive waters systems. Growth should be promoted based on water quality, biodiversity protection, the application of organic inputs, integrated systems of aquaculture, and/or climate-resistant varieties and labor

safety protocols. The scope of this is huge and a premium 'sustainable makhana' certification could put Bihar produce in the high-end export markets.

SUSTAINABLE COMMERCIALIZATION FRAMEWORK

This study proposes the sustainable commercialization framework in five layers. The bottom layer is ecological production – pond based and field-based systems need to protect the water bodies, the biodiversity and reduce unfair chemical use. Integrated makhana-fish systems are recommended as these have diversification of income and better use of resources, when environment allows.

The second layer is farmer aggregation. FPOs/FPCs should bring raw seeds together, negotiate rates, provide access to equipment and primary processing. Aggregation leads to lower transaction costs and the increased viability of mechanized systems. It also enhances traceability as FPOs can keep a record of variety, location, production process and quality.

The third layer is processing and quality infrastructure. Drying, roasting/popping, grading, packaging, moisture control and contamination testing and shelf-life management is done by the cluster level centres. This layer is the most crucial in the process of adding value to raw agricultural output to make it saleable as marketable agricultural products abroad.

Market intelligence and branding is the fourth layer. GI-based positioning needs to be correlated with digital marketing, international buyer connections, food exhibitions, retailers, product innovation, and diversification of categories. Product lines may comprise low fat snacks and flavoured low fat snacks, roasted snacks, makhana flour, breakfast mixes, kheer mixes, nutraceutical blends, children food formulations (as per regulations).

The 5th layer is inclusive governance. All the stakeholders like The Makhana Board, APEDA, Government of Bihar, ICAR-NRC Makhana, NIFTEM, SAUs, FPOs, SHGs, exporters and processors should act as coordinated system to generate innovations. The goal should be to be competitive in the world market with farmer return, not just to grow exports.

CONCLUSION

The future of makhana lies in a disciplined commercialization instead of simply being brandish and use makhana as a superfood commodity in global markets, that can be a reality in Bihar. Important nutritional findings from the study indicate that makhana is an interesting plant-based snack food with functional-food properties due to its low-fat content and low glycemic index. It also reveals a significant

increase in the production and export parameters particularly during the period of 2020-2025. According to correlation and regression results, company size in terms of production, processing capacity and market expansion are the sources with the highest explanatory power regarding export performance, irrespective of the effect of GI branding which is seen as a source of origin differentiation and premium potential.

The key message is that makhana is a viable option somewhere between nutrition, heritage and wetland ecology and rural livelihoods. With having reliable production data, mechanized processing of makhana at the cluster level, quality lab, GI capable traceability, FPO aggregation and export facilitation, Bihar can become a global makhana hub if attains sustainable governance of the wetlands. If these interventions are not taken, makhana could continue to be a good but disjointed business from the farmer's perspective where the value they get is meagre, while for exporters there is an unstable quality. The crop has the potential to boost farmer income, contribute to women empowerment in the enterprise, enhance rural employment, facilitate agriculture in wetland ecosystems with least environmental impact and open the doors for Indian availability in global market of healthy snacks when supported with planning and private sector investment.

LIMITATIONS

The study is subject to some limitations. First, official makhana-specific data at the national level are not complete, particularly for the export value in the previous and older HSN classifications or for pre 2020 exports. Secondly, the regression model makes use of a small data set, as well as constructed indices, and thus the results are exploratory in nature. Finally, they have secondary composition values that vary by variety, processing method, roasting conditions and moisture content for nutrition comparisons. Finally, indicators of sustainability are taken from the literature available and are not measured directly in the field using ecological data. Fifth, projections for the market towards 2035 are based on scenarios and rely on future consumer demand, trade policy, tariffs, logistics infrastructure and quality infrastructure.

FUTURE RESEARCH DIRECTIONS

Future research should create a panel dataset on makhana for various districts based on area, production, yield, farm-gate price, processing margin, exported quantity, and household income. The varieties as well as the roasting methods, glycemic response, phenolics and their shelf-life stability and consumer acceptability should be compared in controlled nutritional studies which include both domestic and international markets. Evaluation of climate resilient

situation, wetland biodiversity, water quality, organic packages and integrated makhana-fish system are worthwhile tasks for agricultural researchers at agro-ecological zones. Management students can learn about the implementation of these branding, e-commerce, the perception of a challenge with a GI as well as how to scale up a start-up. Evaluation of the effects of the Makhana Board, FPO interventions, processing subsidies and programmes for women-led enterprises on farmer value capture should be undertaken by policy researchers.

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