CHAPTER-5

The Economics of Asian Seabass (*Lates calcarifer*) Production in India: Status, Impact and Future Prospects

Geetha R, Abhinaya D, Ravisankar T, Kailasam, M, Jayakumar R, Subburaj R, Shinoj Parappurathu, Rajni Jain, Lal KK and Patil PK

1. Introduction

Fish and fishery products have gained increasing significance as essential food and protein sources, playing a crucial role in providing highly nutritious dietary options for the expanding global population (Naylor et al., 2021). Aquaculture contributes to more than half of the global fish production (182 million tons), underscoring its importance in the context of stagnating captured fish production (FAO, 2022). In India, aquaculture contributes more than 58% to the national fish production of 16.24 million tons (GoI DoF, 2022). In addition to inland water bodies, India is endowed with approximately 1.7 million ha of coastal and 1.2 million ha of potential inland saline area suitable for aquaculture (Geetha et al., 2019). Brackishwater farming is considered one of the potential sources of fish production, food security, economic opportunities, and foreign exchange earnings. Owing to its high commercial value, Asian seabass (*Lates calcarifer*) is one of the most suitable finfish species for diversification of brackishwater aquaculture, which is currently dominated by the monoculture of *Peneaus vannamei*.

The natural geographic distribution of Asian seabass encompasses the tropical Indo-West Pacific region, including the entirety of Southeast Asia, Taiwan extending to Papua New Guinea, and Northern Australia. The global production of Asian seabass is predominantly in Thailand (36%), Malaysia (26%), Taiwan (12%), Saudi Arabia (11%), and India (4%) (FAO, 2022). Asian seabass is regarded as one of the most versatile candidate species for aquaculture in ponds and cages because of its euryhaline nature and adaptability to freshwater, brackish, and marine ecosystems (FAO, 2019). Furthermore, the omnivorous nature of the species facilitates its cultivation using a range of feed sources, from forage fish to formulated diets (FAO, 2020a).

In India, both brackish water and freshwater pond systems are utilized for the production of Asian seabass, either monoculture or integrated with milkfish, tilapia, Indian Major Carps, and other species at commercial scale (CIBA, 2020 and 2022). In commercial seabass farming systems, fingerlings from the nursery are stocked in pre-grow-out ponds, and subsequently, marketable-sized fish are cultivated in ponds and cages for 8 to 16 months (Table 1). Furthermore, cage farming represents an economically viable model, particularly in the backwaters and marine cages of the southern coastal states, owing to the implementation of higher stocking densities, controlled feeding regimens, regular grading, and monitoring protocols (Thirunavukkarasu et al., 2009).

Although India has the potential to emerge as a significant producer of Asian seabass in the region, numerous technical constraints encountered by farmers limit its production. Recent advancements in the year-round production of uniform-sized hatchery fry (Thirunavukkarasu et al., 2015) and specialized formulated feeds for larval, nursery, and grow-out phases (Ambasankar et al., 2009) have resulted in improved survival rates, growth, and feed conversion, thereby enhancing commercial-scale production. These efforts, driven by research organizations and promotional agencies, are anticipated to significantly augment economically sustainable seabass production. In this context, this study provides a comprehensive overview of the current state of Asian seabass aquaculture in India, including its productivity, technical efficiency, challenges, and prospects.

Table 1. General features of different phases in seabass aquaculture

Description	Nursery	Pre-grow-out	Grow-out
Product	Fingerlings	Advanced fingerlings	Marketable size fish
Activity	Fry (1-2 cm) to fingerling (7.5-10 cm)	Fingerlings (7.5-10 cm) to advanced fingerling/juvenile (12-16 cm, 80-100 g)	Advanced fingerling/ juvenile to marketable size fish (>1 kg)
7Duration	60-75 days	60-90 days	8-16 months
Systems	Hapa, tank, small pond	Larger pond, cages	Large pond, cages
Stocking density	40-50/m^2 in pond	Depends on system	Depends on system
	500-1000/m^3 in tank/ RAS		
Survival	50-75%	70-90%	70-90%

2. Data and Methods

2.1 Data

To gather data on cost and returns, production parameters, and socioeconomic characteristics, a comprehensive survey was conducted across major seabass-producing states in India from April 2022 to March 2023 using a purposive sampling approach. The survey encompassed Tamil Nadu (TN), Andhra

Pradesh (AP), and West Bengal (WB) on the east coast, and Kerala (KL) and Karnataka (KA) on the west coast. Districts with significant seabass aquaculture activity were also purposively selected within these states. To ensure data diversity, the seabass farming systems were stratified into nursery (n = 60), pre-grow-out (n = 20), grow-out pond (n = 287), and cage (n = 329) systems. Data were collected through a well-structured interview schedule with farm owners and practitioners engaged in seabass farming.

2.2 Performance Indicators

The technical viability of the system was assessed using stocked seed performance in nursery, pre-grow-out, and grow-out ponds and cages in terms of stocking biomass (g m^{-2}), daily weight gain (DWG, g), percentage weight gain (PWG, %), specific growth rate (SGR, % d^{-1}), feed conversion ratio (FCR), survival (%), duration of the crop (in months), total production (kg ha^{-1} yr^{-1}), and ABW at harvest (g and kg) (Kumaran et al., 2021). Furthermore, the economic and financial viability of Asian seabass farming was evaluated through various economic and growth indicators (Parappurathu et al., 2023), which helps decision-makers assess whether the benefits of the action outweigh the costs, considering the time value of money, and using a common metric to make informed choices (Tables 2 and 3).

2.3 Technical Efficiency: Empirical Model Estimation

Technical efficiency reflects the ability of a production system to obtain the maximal output from a given set of inputs and technology. This study assessed technical efficiency using a stochastic production frontier function approach. Unlike traditional production functions, this method separates deviations from the production frontier into two components: statistical noise (random shocks and measurement errors), and inefficiency relative to the stochastic production frontier (Kumaran et al., 2022).

$$LnY_i = \beta_0 + \sum_{j=1}^{n} \beta_j Ln(X_{ij}) + (v_i - u_i) \ldots\ldots\ldots\ldots (1)$$

where the subscript i refers to the i^{th} farm in the sample; Ln represents the natural logarithm; Y is output variable and X_j is input and related variable, β indicates unknown parameters to be estimated; $\boldsymbol{v}$ is an independent / identical distributed random error having normal distribution N $(0, \sigma_v^2)$ and independent of the u_i; u_i is a nonnegative random variable. The maximum likelihood estimation (MLE) of Eq. (1) provides the estimates of β_s and the variable parameters $\sigma^2 = \sigma_u^2 + \sigma_v^2$ and $\Upsilon = \sigma_u^2 / \sigma^2$.

$$U = \delta_0 + \sum_{j=1}^{n} \delta_j Z_{ij} + W_i \ldots\ldots\ldots\ldots\ldots (2)$$

where Z's are various operational and farm-specific variables; δ's unknown parameters to be estimated; and W_i's are random variables defined by the truncation of the normal distribution with mean 0 and variance σ_u^2. The technical efficiency score for the i^{th} farm in the sample (TE_i), can be defined as

$$TE_i = \exp(-u_i) \quad \text{............ (3)}$$

TE_i scores ranged from 0 to 1. A firm with a score of 1 indicates that it lies on the production frontier and utilizes inputs both technically and efficiently. Lower scores indicate greater inefficiency. The analysis was performed using R Studio version 4.2.3.

Table 2. Performance indices of Asian seabass production

Economic Indicators	
Net operating ratio	$\frac{\text{Operating costs}}{\text{Gross income}} * 100$
Return on Investment (ROI)	$\frac{\text{Gross income} - \text{total cost}}{\text{Total Cost}} * 100$
Benefit Cost Ratio (BCR)	$\frac{\sum_{t-1}^{n} \text{Present value of future benefits}}{\sum_{t=1}^{n} \text{Present value of future costs}}$
Net Present Value (NPV)	$\sum_{t=1}^{n} \left(\frac{CF_t}{(1+r)^t}\right)$ - Initial investment CF_t represents the cash flow at time t r is the internal rate of return t is the time period
Internal Rate of Return (IRR)	$\sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} = 0$
Break-even point	$\frac{\text{Total fixed cost}}{(\text{Sales price per unit} - \text{Variable cost per unit})}$
Break-even price	$\frac{\text{Total fixed cost}}{\text{Total Production}} + \text{Variable cost per unit}$
Growth Indicators	
Daily Weight Gain (DWG)	$\frac{(\text{Mean final weight} - \text{Mean initial weight})}{\text{Duration in days}}$
Weight Gain (PWG)	$\frac{(\text{Mean final weight} - \text{Mean initial weight})}{\text{Mean initial weight}} * 100$
Specific Growth Rate (SGR)	$\frac{(\ln(\text{final weight}) - \ln(\text{initial weight}))}{\text{rearing duration in days}} * 100$

Table 3. Description of performance indices

Indicators	Description
Economic indicators	
Operating Cost Ratio	• The net operating ratio is the proportion of the gross income covering operating expenses • A firm with an OCR below 1 is profitable on an operating basis, while an OCR higher than 1 indicates an operating loss.
Return on Investment (ROI)	• ROI compares how much you paid for an investment to how much you earned to evaluate its efficiency.
Benefit Cost Ratio (BCR)	• The BCR compares the present value of future benefits generated from the farm to the present value of future costs. A BCR greater than 1 signifies that the farm's expected future benefits exceed its costs, indicating it is economically viable.
Net Present Value (NPV)	• The NPV is the main criterion for assessing the suitability of any investment program and according to this financial indicator, the greater is its value, the higher will be the convenience of the investment.
Internal Rate of Return (IRR)	• The IRR is the discount rate at which the discounted benefits are equal to the discounted costs, determining a net present value equal to zero. • It is the annual growth rate that a farm is expected to generate. It is used to understand the profitability and earnings of the farm
Break-even point	• The break-even point is the amount of production volume a farm needs to reach a state where total revenue equals total costs. After reaching the break-even point, revenues above the fixed and variable costs will become profit.
Break-even price	• The break-even price refers to the unit price a product must sell at for total revenue to equal total costs. At the break-even price, no loss or gain is made per unit sold.
Growth Indicators	
Daily Weight Gain (DWG)	• It refers to the average daily increase in body weight of fish over a specific time period. Higher daily gains equate to better feeding efficiency and faster growth to market size.
Weight Gain (PWG)	• It provides a standardized comparison of growth between different culture environments and management methods, independent of differences in initial body size. Higher percent gains over a defined period equate to faster rates of growth.
Specific Growth Rate (SGR)	• It is a measure used to quantify the percentage increase in body weight of cultured fish per day. It allows standardized comparisons of growth performance between groups under different experimental or production conditions over time.

2.4 Time Series Forecasting

To forecast Indian Asian seabass production, different time series models such as naive forecast, simple exponential smoothing, Holt's trend method, and autoregressive integrated moving average (ARIMA) were evaluated using model evaluation metrics, such as the Akaike Information Criterion (AIC), Corrected Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), Mean Percentage Error (MPE), Mean Absolute Percentage Error (MAPE), and Mean Absolute Scaled Error (MASE) (Stergiou, 1991). The ARIMA model (1,1,0) was selected to forecast seabass production. Residual diagnostics such as the Box L-Jung test for serial correlation, one-sample Kolmogorov-Smirnov test, and the Anderson – darling test for normality were conducted.

2.5 Constraint Analysis:

The constraints perceived by respondents in seabass farming were prioritized using the Garrett ranking technique. The orders of merit assigned by respondents were converted into ranks using the following formula:

$$\text{Percent position} = \frac{100\left(R_{ij} - 0.5\right)}{N_j}$$

where R_{ij} is the rank given for the i^{th} item by the j^{th} individual and N_j is the number of items ranked by the j^{th} individual. The scores were averaged across respondents to determine the final ranks. This method allowed the quantified prioritization of key technical, economic, and social constraints impacting the sustainability of seabass farming practices. (Garrett and Woodworth, 1969)

2.6. SWOT Analysis

An assessment of strengths, weaknesses, opportunities, and threats (SWOT) was conducted to understand the internal and external factors affecting the sustainability of Asian seabass aquaculture. The analysis was conducted based on primary data collected through key informants and focus group discussions with seabass farmers, experts from the ICAR-CIBA and state fisheries departments, hatchery operators, seed suppliers, feed manufacturers, and other aquaculture value chain participants across the study area.

3. Results and Discussion

3.1. Socio-Economic Dimensions of Seabass Farming

Demographic information, regional differences, and gaps in production systems facilitate the development of appropriate interventions to promote seabass farming. Farmers engaged in nursery rearing were predominantly middle-aged (40%) and educated individuals. The majority (58%) had limited experience (<5 years) and more than half of the family members were reported to be involved in farming activities. Similarly, pre-grow-out culture was predominantly practiced by middle-aged (50%) and highly experienced (65%) farmers. Sustainability of nursery (7.5 years) and pre-grow-out (10 years) activities were observed through permanence in these practices. Most farmers involved in nursery and pre-grow-out operations had undergone formal training and pursued it as a primary occupation, relying predominantly on self-financing (Table 4).

Pond culture of Asian seabass is predominantly practiced in Andhra Pradesh and West Bengal. Farmers from these states possessed higher educational qualifications and experience, demonstrated better capital self-sufficiency, exhibited greater reliance on family labor, and participated more frequently in formal training. Notably, the permanence of activity was higher in these regions. More than half (52%) of the farmers in Andhra Pradesh were engaged in seabass culture as their primary occupation (Table 4).

Similarly, the grow-out cage culture of Asian seabass is predominantly practiced in Tamil Nadu, Kerala, and Karnataka. Farmers in these states reported higher secondary education, high capital self-sufficiency, approximately half of the family labor involvement, and up to 60% had formal training. Nearly half of them considered seabass farming to be their primary activity. In a recent study, the reported self-sufficiency was consistent with that in the present study for the state of Kerala, whereas it was comparatively lower in other cages (Parappurathu et al., 2023). However, approximately half of the farmers in Tamil Nadu and Kerala have extensive experience (> 10 years). The longest duration of activity was observed among Karnataka farmers (eight years) compared to their counterparts in Kerala (seven years) and Tamil Nadu (three years) (Table 4). In a similar study, a longer duration of activity was reported in seabass cage farming in Kerala and Karnataka (five years) and Tamil Nadu (1.7 years) (Parappurathu et al., 2023).

Table 4. Socio-economic dimensions of seabass farming under various production systems

Parameters		Nursery	Pre-grow-out	Grow-out				
				Pond culture		Cage culture		
				Andhra Pradesh	West Bengal	Tamil Nadu	Kerala	Karnataka
Age (%)	Young (upto 30 years)	35.00	25.00	11.00	10.00	11.00	10.00	7.98
	Middle-aged (31-45 years)	40.00	50.00	54.00	39.00	39.00	50.00	57.75
	Old-aged (>45 years)	25.00	25.00	35.00	51.00	50.00	40.00	34.27

Parameters		Nursery	Pre-grow-out	Grow-out				
				Pond culture		Cage culture		
				Andhra Pradesh	West Bengal	Tamil Nadu	Kerala	Karnataka
Education (%)	Primary schooling (<5)	25.00	25.00	25.00	23.00	0.00	0.00	38.97
	Secondary schooling (6-12)	35.00	45.00	71.00	72.00	64.00	73.00	56.34
	University	40.00	30.00	4.00	5.00	36.00	27.00	4.69
Secondary occupation (%)		98.33	100.00	48.36	70.10	57.81	55.61	48.35
Permanence in activity (PA)*		7.58 (4.47)	9.9 (3.68)	14.70 (6.30)	16.84 (10.66)	2.97 (0.83)	6.86 (3.97)	8.14 (3.84)
Experience (%)	Low (<5 years)	58.33	20.00	41.75	20.65	17.19	19.23	31.92
	Medium (5 - 10 years)	11.67	15.00	47.57	13.59	28.13	38.46	33.33
	High (> 10 years)	30.00	65.00	10.68	65.76	54.69	42.31	34.74
Capital self-sufficiency (CS) (%)		81.67	65.00	68.75	78.25	69.55	74.32	61.50
Family labor share (FL) (%)		54.92	44.23	51.00	53.43	41.20	44.05	46.51
Formal training (FT) (%)		45.00	40.00	68.00	63.00	59.00	64.00	55.39

Note: Figures in parentheses indicate standard deviations.

3.2. Economics of Different Fish Farming Systems

Economic analysis of different culture systems provides insights into the viability and profitability of seabass farming. The cost and returns of the nursery, pre-grow-out, and grow-out (pond and cage) farm operations are expressed in Rupees per hectare per year (Rs $ha^{-1}yr^{-1}$), while cage culture in Rupees per cubic meter per year (Rs m^{-3} yr^{-1}). To estimate the fixed costs, depreciation of machinery and interest in capital investment were calculated at 10% and 12%, respectively (Table 5).

3.2.1. Nursery

Seabass nurseries in India are predominantly situated in Krishna district of Andhra Pradesh. These nurseries obtained seeds from both hatcheries and wild collections from adjacent bays and backwaters in Andhra Pradesh (Machilipattinam, Krishna district) and West Bengal (North and South 24 Parganas). Three rearing cycles are typically conducted annually (May-July, September-November, and December-March), primarily using naturally available zooplankton from brackish water creeks as feed. Economic analysis of the fish nurseries revealed substantial profitability (Table 5). Notwithstanding the initial investment and annual operational costs, the nurseries demonstrated robust return on investment, underscoring the viability of fish farming as an appropriate agricultural enterprise, particularly in regions with suitable water resources.

3.2.2. Pre-grow-out

The pre-grow-out farms were located at an average distance of 1.64 km from the farmer's home, with 0.88 acres of a spread area and an average pond size of 0.56 ha. These farms are engaged in fish production throughout the year. Seeds were procured from a considerable distance, weighing 4.6 grams each, and were purchased at ₹19.75 per seed. Forage fish priced at ₹ 27 per kilogram was the primary feed. Harvested fish, weighing an average of 108.6 grams, were sold for ₹ 111.45 per fish. The analysis of pre-grow-out farms demonstrates a profitable venture in the aquaculture industry, achieving a substantial net profit. The high survival rate and multiple (3) crop cycles have contributed to this profitability. However, careful management and risk mitigation strategies are crucial for ensuring long-term sustainability and success in pre-grow-out aquaculture

3.2.3. Grow-out pond system

To understand the economic viability of grow-out pond cultures, this study focused on the major seabass production states in Andhra Pradesh and West Bengal. In Andhra Pradesh, seabass farms were located an average of 5.54 km from farmers' homes, with an average farm area of 2.96 ha and a water spread area of 2.37 ha. Each pond averaged 2.26 acres, and fish were reared throughout the year. The average capital investment in seabass aquaculture in the state was substantial, with major expenditures on leases, farmhouses, machinery, and equipment. Fixed annual costs are largely driven by lease payments and pond construction, whereas operational costs are dominated by feed, accounting for 51.1% of the total cost at ₹ 25 kg-1. Most grow-out farmers use low-value fish such as tilapia, sardines, and minor carps as feed for seabass. This finding is similar to that reported by Young et al. (2020). Labor costs, at ₹14,270 per man-month, accounted for 21.66 man-months per hectare, representing 8.73% of the total cost. Similar to studies in Sri Lanka (Gammanpila and Singappuli, 2014) and Vietnam (Nhan et al., 2022), operational costs (88.20%) dominated the total cost (Fig. 1a). Despite these high costs, the sector remains economically viable, as evidenced by its high profitability (Fig. 1c). Profitability is further supported by the use of affordable feed sources and efficient management of labor costs.

Similarly, seabass farms in West Bengal are typically situated 1.94 km from homes, covering an average of 0.99 hectares with 0.78 hectares of water spread area. Farms contained an average of 2.65 ponds, each measuring approximately 0.42 hectares, and were farmed throughout the year. The average capital investment for seabass culture ponds was ₹59 thousand per ha per year, with significant fixed costs for lease and pond construction. Fingerlings (80.15 g) were procured from wild collection points located 40.33 km away for ₹13.38 per seed. The average stocking biomass was 11.89 g m^{-2}, primarily relying on natural feed. Given the large confined water bodies and abundant live fish availability in West Bengal (Ghosh, 2019), as well as the practice of bait fish feeding (Ghosh et al., 2022), farmers in this region predominantly depend on natural feeding. Farm labor represented the highest operational cost at 46.86% 9 (Fig. 1a), with farms utilizing approximately 24 man-months at an average monthly wage rate of ₹14, 220. Despite these expenses, farms achieve a solid production yield and generate substantial gross and net incomes, demonstrating the economic viability of seabass farming in this region (Fig. 1c).

Seabass aquaculture practices and production performance differed between Andhra Pradesh and West Bengal. Culture operations in Andhra Pradesh demonstrated intensive systems with high input costs, but higher productivity and profitability. Farm production was three times higher in Andhra Pradesh than in West Bengal, which could be attributed to multiple factors, such as stocking of uniform-sized hatchery seeds, higher stocking biomass, greater survival rates, longer crop duration (484 days), and relatively higher daily weight gain (8.01 g), PWG (3259.59 %), ABW at harvest (3.99 kg), and proximity to all three phases. In addition, the superior production outcomes in the Andhra Pradesh ponds were enabled by substantially higher capital investment and operating expenditures. The cost of production in Andhra Pradesh was over 3.5 times that in West Bengal. However, the intensive use of inputs translated into far higher gross income. Overall, the intensive and advanced farming techniques employed in Andhra Pradesh showed significantly higher productivity and profitability, albeit requiring greater capital investments and higher operating expenses. The introduction of commercially available formulated feeding practices and stocking hatchery-produced weaned fry along with training and technical assistance to West Bengal farmers could help in realizing higher production capacities.

3.2.4. Grow-out cage system

Since most cages are situated in Kerala, followed by Karnataka and Tamil Nadu, we studied the economic viability of grow-out cage cultures in these states. Farmers typically own single cage and culture seabass throughout the year in Tamil Nadu, utilizing circular floating cages with an average volume of 113.04 m^3. Acquiring seabass seeds is a constraint because stackable-sized fingerlings/juveniles were sourced at an average distance of 475 km. The average stocking biomass was 438.78 g m^{-3} (51.68 g nos^{-1}), costing approximately ₹40 per seed. The feed was the largest operational cost component, comprising 57.25% of the total (@ ₹32 kg^{-1} of low-value fish), which was in accordance with previous findings in seabass cage farming in the Black Sea in Turkey (Bozoglu and Ceyhan, 2009). Labor costs made for 22.61% of the total cost. Farms utilized 12 man-months of labor per cage, with workers earning an average monthly wage of ₹14,683. Operational costs accounted for 88.73% of the total annual production costs (Fig. 1b). Cages yielded an average of 20 kg m^{-3} (84.89% survival rate), which is comparable to the previously reported 22 kg m^{-3} (Bozoglu and Ceyhan, 2009). Despite operational costs, the net profit indicates the economic viability of cage aquaculture (Table 5, Fig. 1d). These results highlight the potential of cage farming as a sustainable and profitable method of fish production.

Seabass cage farms in Kerala are typically located 2.25 km from the farmers' homes. Each farm operated an average of seven cages, with an individual cage volume of 48 m^3. The annual capital investment averaged ₹4,889 m^{-3} year^{-1}, covering cage frames, farmhouses, and equipment costs. Procurement of seeds poses a challenge, as stackable fingerlings/juveniles are sourced at an average distance of 1,072 km. Stocking density averages one Kg m^{-3} (52.55 g nos-1), with each fingerling costing ₹ 40. Procurement of seeds poses a challenge, as stockable-size fingerlings/juveniles are sourced at an average distance of 1,072 km. Despite significant operational costs, particularly feed and labor, farms demonstrate a positive return on investment. The average annual yield of 27 kg m^{-3} coupled with a survival rate of 75.80% indicates the efficiency of the cage culture system. The sale of harvested fish for ₹ 500 kg^{-1} generates substantial gross income, leading to a net profit of ₹ 3,966 m^{-3} (Table 5, Fig. 1d). Although feed constitutes the largest expense, optimizing feeding strategies and exploring alternative feed sources could help reduce costs. Additionally, improving labor efficiency and exploring cost-effective labor practices could further enhance profitability.

The cage farms in Karnataka were typically situated 2.18 km from farmers' homes. Farms operate an average of 1.2 cages per farm with an individual cage volume of 90.72 m^3. The average annual capital investment is ₹ 1,246 m^{-3} year$^{-1,}$ which includes the costs of the cage, farmhouse, and equipment. The resulting fixed operational costs of ₹ 275 m^{-1} year^{-1} were due to depreciation and interest payments. As most hatcheries are in Andhra Pradesh, acquiring seeds was the major constraint adding to the cost of the seed. The stocking biomass averaged 960 g m^{-3} (37.79 g nos^{-1}) costing ₹ 35 per seed representing 25.66% of operational expenses. While feed remains the major cost in seabass farming (Fig. 1b), accounting for over half of the total costs, the operation remains profitable, achieving notable gross income and net profit (Parappurathu et al., 2023) (Table 5, Fig. 1d).

Seabass cage farming has demonstrated commercial viability. In Kerala, the scale is smaller but with higher production levels and good survival rates of 75.8% from a moderate stocking density. This translates into an annual profit of approximately Rs 4,000 m^{-3}, partly aided by the slightly lower feed costs. In comparison, Tamil Nadu farmers run larger floating cages and achieve higher absolute yields. In a controlled experimental study on three-tier cage farming, Kumaran et al. (2021) reported an average productivity of 13.5-15.0 kg m^{-3}. However, larger cages and greater stocking incur higher operational expenses, especially for feed and labor, squeezing annual net profit to around Rs 2,000 m^{-3}. Karnataka represents smaller-scale farming with low fry density and modest productivity with a survival rate of 23%. The fixed costs are low, with annual profits of approximately Rs 2,500 m^{-3}. Across states, feed efficiency, seed availability, and survival impact outcomes, Kerala currently demonstrates superior production performance and economics from its cage models. In a site-specific study, a similar cost of feed was observed in all three stages, whereas the cost of seed was higher (Kumaran et al., 2021).

Across all farming models, feed and seeds were the major recurring costs. However, location-specific factors such as productivity, input costs, and market prices contribute to differences in profitability variations between states. Optimizing feed, improving survival and growth, and adopting an appropriate farm size could positively impact returns. Overall, the results validate seabass aquaculture as a profitable livelihood avenue under optimal management.

Table 5. Cost and returns of seabass farming in India

Parameters	Nursery (Rs ha-1 yr-1)	Pre-grow-out (Rs ha-1 yr-1)	Grow-out				
			Pond culture (Rs ha-1 yr-1)		Cage culture (Rs m-3 yr-1)		
			Andhra Pradesh	West Bengal	Tamil Nadu	Kerala	Karnataka
A. Fixed cost							
Capital investment	2,53,464	1,46,244	9,70,821	59,503	3,994	4,889	1,246
Lease	96,818	85,930	1,90,595	59,503	-	-	-
Pond construction	44,250	33,313	36,595	71,551	-	-	-
Depreciation @ 10%	5,200	2,700	74,363	55,684	399	489	124
Interest on capital cost @12 %	30,416	5,197	1,16,498	82,548	479	587	149
Total fixed cost/crop	1,76,683	1,27,141	4,18,052	2,69,285	878	1,076	275
B. Operational Cost							
Seed	3,12,776	4,80,156	4,30,642	28,973	339	764	744
Feed	0	3,07,370	15,96,613	0	4,003	4,778	1,586
Labor	99,310	1,42,496	3,09,180	3,41,843	1,563	935	152

Parameters	Nursery (Rs ha-1 yr-1)	Pre-grow-out (Rs ha-1 yr-1)	Grow-out				
			Pond culture (Rs ha-1 yr-1)		Cage culture (Rs m-3 yr-1)		
			Andhra Pradesh	West Bengal	Tamil Nadu	Kerala	Karnataka
Pond operation cost	79,729	91,026	85,875	1,53,073	-	-	-
Miscellaneous expenses	81,187	58,697	3,67,565	1,27,489	314	1,084	102
Interest on working capital @ 12%	68,761	1,29,569	3,34,785	78,165	740	907	315
Total operational cost	6,41,764	12,09,315	31,24,659	7,29,542	6,914	8,468	2,899
Total cost (A+B)	8,18,447	13,36,456	35,42,711	9,98,827	7,792	9,543	3,173
Production (kg)	2,566	2,111	13,677	4,263	20	27	14.13
Gross Income	12,61,167	21,67,606	60,22,599	18,73,730	9,980	13,510	5,652
Net income	4,42,719	8,31,151	24,44,498	8,98,605	2,187	3,966	2,479

Fig. 1a. Economics of seabass production in grow-out pond culture

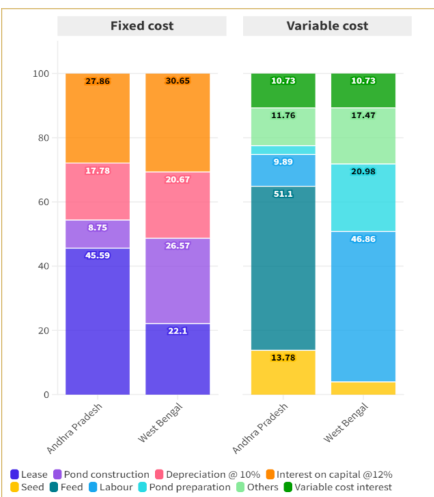


Fig. 1b. Economics of seabass production in grow-out cage culture

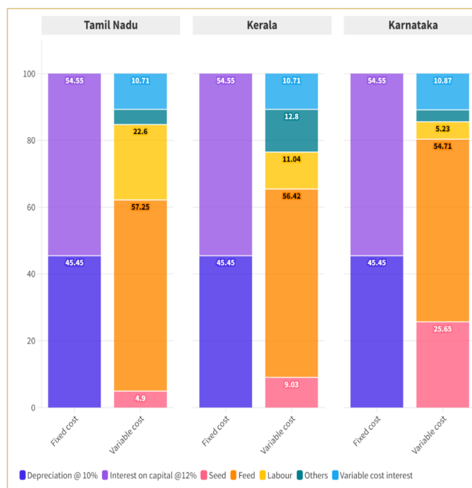


Fig. 1c. Cost and returns of seabass culture in grow-out pond culture

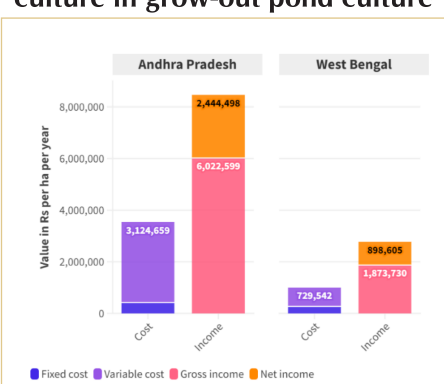
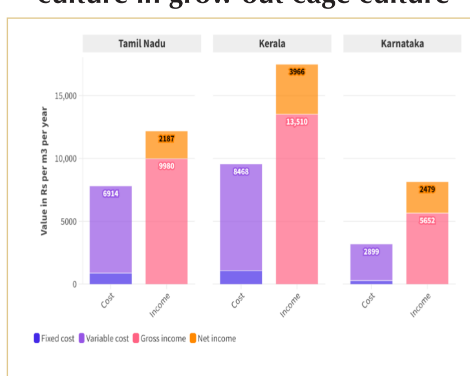


Fig. 1d. Cost and returns of seabass culture in grow-out cage culture



3.1.5. Performance indicators of seabass production

Among the farming systems studied, nurseries had the highest operating cost ratio (78.41%), followed by cage culture (50-70%), pre-growth out, and pond culture. Conversely, pond culture exhibited the highest return on investment (ROI) at 70-88%, followed by pre-grow-out and cage culture. The observed operating cost ratio in the present study was similar to the previously reported ratio of 57-58% in Kerala cage culture (Aswathy and Imelda, 2018). However, grow-out cages in Karnataka demonstrated a significant improvement in ROI (78.14%) compared with the previously reported 31.79% (Ail and Bhatta, 2016). The lower operating cost ratio in pond culture in West Bengal, resulting in a higher ROI, may be attributed to traditional farming practices, stocking wild seeds requiring less input, and lower management costs. In contrast, the higher operating costs in AP farms due to the intensive stocking of nursery-reared fingerlings resulted in a comparatively lower ROI. A similar study in Vietnam by Nhan reported that increased stocking density led to higher total revenues and production costs, but decreased capital efficiency. Nursery farmers achieved break-even at a biomass of 731 kg ha^{-1} (28.80% of the reported production) and a price of ₹ 319 Kg^{-1}, while pre-grow-out systems reached break-even at a biomass of 288.11 Kg ha^{-1} (13.64%) and a price of ₹ 633 Kg^{-1}. In grow-out pond culture, Andhra Pradesh farms reached break-even earlier at 1,545 kg ha^{-1} (11.29% yield) than West Bengal at 1,416 kg ha^{-1} (33.22% yield). Similarly, in cage culture, Karnataka farms achieved break-even earlier at 2.01 Kg m^{-3} (14.22% yield) as compared to Tamil Nadu and Kerala farms (Table 6).

The average crop duration for the seabass nurseries was 2.3 months, stocked at a density of 5.19 g m^{-2} and recorded a production of 61,073 nos ha^{-1} yr^{-1}. Similarly, pre-grow-out farms stocked at 50.38 g m^{-2} achieved a calculated daily weight gain of 1.20 g, and produced 2110.92 Kg ha^{-1} yr^{-1}. With higher stocking biomass (62.73 g m^{-2}), survival rates (87.20%), crop duration (16.14 months), higher daily weight gain (8.01 g), PWG (3259.59 %) and ABW at harvest (3.99 kg), grow-out farmers in Andhra Pradesh produced 13.67 t ha^{-1} yr^{-1} as compared to West Bengal, which reported productivity of 4.26 t ha^{-1} yr^{-1} with 71.57% survival rate. The average biomass harvested in the cages of Tamil Nadu was 19.91 Kg m^{-3} yr^{-1} (ABW at harvest, 2.76 kg) with 84.89% survival rate, FCR of 6.33, daily weight gain (7.51 g), PWG (5247.64%), and SGR (1.11), whereas Kerala with higher stocking biomass (988 g/m^2) achieved a higher productivity of 27.04 Kg m^{-3} yr^{-1}. In a previous study, Kumaran et al. *(2021)* also reported a similar daily weight gain in pre-grow-out (1.21 g d^{-1}) and grow-out cage (4.33 g d^{-1}) cultures. However, in Karnataka, the performance of key technical indicators was low compared to Kerala and Tamil Nadu, although they stocked high biomass, resulting in lower productivity among cages (Table 6).

Table 6. Performance indicators of seabass farming in India

Indicators	Nursery	Pre-grow-out	Grow-out				
			Pond culture		Cage culture		
			Andhra Pradesh	West Bengal	Tamil Nadu	Kerala	Karnataka
Technical indicators							
Stocking biomass (g m-2)	5.19 (0.47)	50.38 (2.85)	62.73 (5.74)	11.89 (1.79)	438.78 (74.49)#	988.04 (198.76)#	963.56 (271.46) #
FCR	-##	5.43 (0.38)	5.80 (0.37)	-##	6.33 (0.32)	6.28 (0.44)	5.39 (0.54)
Survival (%)	81.35 (2.43) 78.00-85.00	84.55 (2.58) 80.00-88.00	87.20 (4.48) 80.00-95.00	71.57 (9.64) 53.00-90.00	84.89 (3.13) 80.00-89.00	75.80 (4.59) 68.00-86.25	72.76 (4.48) 70.00-80.00
Duration (Month)	2.32 (0.20)	2.97 (0.06)	16.14 (1.49)	8.23 (0.46)	12.03 (1.18)	12.23 (1.02)	12.02 (0.04)
ABW at harvest (g)	41.56 (2.11)	108.62 (5.89)	3.99 (0.56)**	1.89 (0.39)**	2.76 (0.23)**	1.87 (0.51)**	1.17 (0.12)**
Production (Kg ha-1 yr-1)	2537.61 (173.13)	2110.92 (112.80)	13676.78 (2198.25)	4262.58 (666.36)	19.91 (2.48)*	27.04 (7.78)*	14.06 (1.46)*
DWG (g)	0.53	1.20	8.01	7.36	7.51	4.97	3.09
PWG (%)	842.53	6687.50	3259.59	2268.825	5247.642	3474.82	2985.927
SGR (% d-1)	3.08 (0.29)	4.80 (0.81)	0.73 (0.07)	1.28 (0.13)	1.11 (0.11)	0.97 (0.09)	0.90 (0.01)
Economic and Financial indicators							
Operating cost ratio %	78.41	55.79	51.88	38.93	69.28	62.68	51.28
Return on Investment %	54.09	62.19	69.99	87.59	28.06	41.55	78.14
Break-even point (Kg)	731.13	288.11	1,545.21	1,416.26	5.70	5.76	2.01
Break-even price (Rs kg-1)	319.15	633.11	200.36	312.61	391.39	352.82	220
BC ratio	1.54	1.62	1.69	1.87	1.28	1.41	1.78
Net Present Value (Rs)	19,58,525	24,56,716	76,13,381	31,02,185	5,986	13,215	2,263
Internal rate of return (%)	51.00	59.86	67.00	89.00	51.81	80.00	81.00

*Note: '**' at 1%; '*' at 5%; # - indicates stocking biomass per m3; ##- indicates live feed; *- indicates production in Kg m-3 yr-1; **- indicates weight per unit in kg. The figures in parentheses indicate the standard deviations.*

A higher IRR, positive NPV, and BCR (>1) were observed for different seabass production systems, which is in line with earlier findings (Ravisankar et al., 2010; Aswathy and Imelda, 2018; Kumaran et al., 2021). The observed higher BCR, NPV, and IRR demonstrate that the pre-grow-out system is financially more viable and profitable than the nursery system. In pond culture, while

West Bengal had higher BCR and IRR, AP farms recorded a higher NPV of Rs 7600 thousand ha^{-1} yr^{-1}. In cage culture, Karnataka farms exhibited higher BCR and IRR than Tamil Nadu, and Kerala and also demonstrated higher NPV and IRR. Overall, pond production models generated better return and profitability metrics than cage models. Among pond production models, WB showed better efficiency in terms of BC ratio, ROI, and operating costs, whereas AP performed best in metrics such as break-even point and NPV. Among the cage models, Karnataka and Kerala performed economically better across most metrics. To compare productivity per unit area (ha), the costs and returns for both pond and cage farming were analyzed. For the calculations, 50 cages of 100 m^{-3} were assumed. The analysis found that cage culture grow-out recorded higher total cost, but also resulted in a higher income and net income per hectare. However, pond culture had a higher profit per ton of production (Table 7)

The production economics of major Asian seabass aquaculture systems provides important insights. Nursery and pre-grow-out ponds perform better financially, with superior profitability metrics, benefiting from lower costs and higher biomass yields. Among grow-out cultures, ponds in Andhra Pradesh demonstrate higher operating costs and lower ROI, whereas West Bengal ponds can achieve higher BCR and return on investment. Cage culture exhibits variability across states, although Karnataka farms can reach break-even more quickly. Additionally, the study highlights diversified cost structures, break-even points, and profitability profiles across multiple farming systems. These dynamics could help farmers to select appropriate models and inform targeted strategies to improve their financial and economic viability. Overall, this analysis provides robust economic insights to support upgraded Asian seabass aquaculture practices and commercial progress. Further investigation of innovative technologies and integrated culture systems may offer additional opportunities for improved production performance and profitability.

Table 7. Comparison of output between pond and cage culture of seabass

Particulars	Pond	Cage (50) (Hypothetical)	Pond	Cage
	(Rs thousands ha-1 yr-1)		(Rs thousands t-1 yr-1)	
Seed	431	1695	31	19
Feed	1597	20015	117	222
Labor	309	7815	23	87
Others	789	5045	58	56
Total variable cost	3125	34570	228	384
Total fixed cost	418	4390	31	49
Total cost	3543	38960	259	433

Particulars	Pond	Cage (50) (Hypothetical)	Pond	Cage
	(Rs thousands ha-1 yr-1)		(Rs thousands t-1 yr-1)	
Production (t)	1368	9000	-	-
Gross Income	6023	45000	440	500
Net income	2444	6040	179	67

3.2.6 Technical efficiency using stochastic frontier production function

To assess the efficiency of the farms in grow-out production systems, we employed a stochastic frontier production function. The analysis revealed a positive and significant ($P<0.001$) influence of several variables on pond production, including survival rate (0.84), crop duration (0.79), stocking density (0.67), and initial weight (0.76). Improving these variables leads to increased technical efficiency (Table 8a). Similarly, in grow-out cages, survival rate (0.77), crop duration (0.47), stocking density (0.75), and stocking weight (0.72) had a significant ($P<0.001$) positive effect on technical efficiency (Table 8b). Previous studies by Pushpalatha et al. (2021) and Kumaran et al. (2022) have also reported the influence of stocking density and survival on production. Additionally, experience and education positively impacted efficiency in pond and cage culture systems, respectively.

Table 8a. Maximum likelihood estimates of stochastic frontier production function in pond system.

Parameters	Estimate	Std. Error	z value	Pr(>|z|)
Technical Efficiency				
Intercept	-5.193	1.201	-4.324	0.000***
Survival (%)	0.844	0.217	3.893	0.000***
Duration of crop (in months)	0.794	0.068	11.698	0.000***
Feed (Kgs)	-0.037	0.070	-0.527	0.598
Stocking density (Nos m^{-3})	0.670	0.133	5.053	0.000***
Stocking weight (g)	0.761	0.067	11.409	0.000***
ABW at harvest (Kg)	0.077	0.070	1.099	0.272
Inefficiency				
Intercept	-1.610	0.839	-1.918	0.055#
Experience	-0.085	0.040	-2.122	0.034*
Education	0.160	0.072	2.243	0.025*
Age	0.380	0.208	1.823	0.068#
Household size	-0.014	0.074	-0.183	0.855
Sigma Sq	0.091	0.014	6.650	0.000***
Gamma	1.000	0.001	761.725	0.000***
Log-likelihood ratio: 142.605				

*Note: '***' denotes significance at 0.1%; '**' at 1%; '*' at 5%; '#' at 10%.*

Table 8b. Maximum likelihood estimates of stochastic frontier production function in the cage system.

Parameters	Estimate	Std. Error	z value	Pr(>|z|)
Technical Efficiency				
Intercept	-4.895	0.988	-4.957	0.000***
Survival (%)	0.770	0.199	3.871	0.000***
Duration of crop (in months)	0.467	0.086	5.431	0.000***
Feed (Kgs)	0.039	0.052	0.741	0.459
Stocking density (Nos m^{-3})	0.747	0.057	13.197	0.000***
Stocking weight (g)	0.718	0.078	9.163	0.000***
ABW at harvest (Kg)	0.065	0.034	1.876	0.061#
Inefficiency				
Intercept	-0.357	0.980	-0.364	0.716
Experience	0.020	0.804	0.025	0.980
Education	-0.433	0.238	-1.819	0.069#
Age	0.309	0.592	0.523	0.601
Household size	-0.146	0.173	-0.846	0.397
Sigma Sq	0.179	0.022	8.078	0.000***
Gamma	0.999	0.001	713.547	0.000***
Log-likelihood ratio: 38.1712				

*Note: '***' denotes significance at 0.1%; '**' at 1%; '*' at 5%; '#' at 10%*

The grow-out cage and pond cultures exhibited higher mean technical efficiencies (82.08% and 80.93%, respectively), with a larger proportion of farms falling into the very high technical efficiency category (Fig. 2), suggesting expertise among farmers in these systems. However, a significant portion (38%) of pond culture farms operate at medium efficiency and require continued training and technical assistance to optimize production (Fig. 2). In conclusion, key variables such as survival rate, crop duration, stocking density, stocking weight, and socioeconomic factors such as higher education and experience drive higher technical efficiency. Table 9 outlines the factors influencing sustainable aquaculture practices.

Fig. 2. Proportion of farms under various technical efficiency categories per m^3 per year

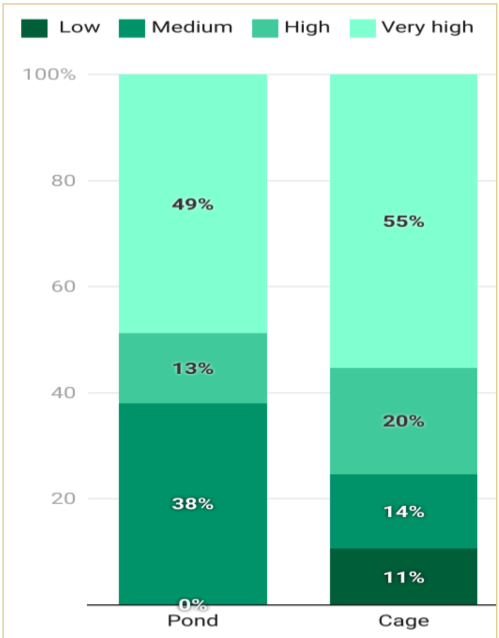


Table 9. Factors influencing sustainable practices in seabass culture

Parameters		Nursery	Pre-grow-out	Grow-out				
				Pond culture			Cage culture	
				Andhra Pradesh	West Bengal	Tamil Nadu	Kerala	Karnataka
Adoption of scientific farming practices (%)	Non-adoption	32.44	15.00	10.05	19.21	9.76	8.75	12.57
	Less than 5 years	27.46	26.45	39.25	48.29	21.34	20.30	26.25
	5-10 years	15.45	10.70	42.45	14.25	22.45	28.46	33.33
	>10 years	24.65	47.85	8.25	18.25	46.45	42.49	27.85
Extension services (%)		84.55	78.95	88.75	73.25	76.35	81.00	83.25
Interaction with Research Institutes (%)		68.75	74.55	82.45	45.55	72.00	76.45	72.45
Farming continuity (%)		95.00	98.45	100.00	89.00	100.0	97.00	95.67

3.2.7 Estimation of seabass production

Based on the primary data collected in this study, the annual production of seabass fry in India was estimated to be 4.98 million, including 1.98 million from six seabass hatcheries. Considering an average body weight at harvest of 2.43 Kg and a survival rate of 78.59%, the total production of Asian seabass in 2022 is estimated to be 7,544 tons. However, the FAO aquaculture report for 2022 listed India's seabass production at 5,700 tons, while MPEDA reported 4,754 tons (MPEDA, 2022). Using national seabass production data from 2010 to 2022 (FAO Fish Database), we forecast future seabass production in India using the ARIMA (1,1,0) model. Residual diagnostics, including the Box-Ljung test, one-sample Kolmogorov-Smirnov test, and the Anderson-Darling test, confirmed a better fit of the model (Table 10). The model predicts that seabass production will reach 11,317 tons in 2025 (Table 11, Fig. 3).

Table 10. Results of residual diagnostics for ARIMA (1,1,0)

Test	Statistic	P-value
Box L-jung	13.773	0.1836
Shapiro-Wilk	0.8388	0.0457
Kolmogorov- smirnov	0.2309	0.4918
Anderson- Darling	0.9401	0.1186

Table 11. Forecast of Seabass production using Auto-Regressive Integrated Moving Average (ARIMA)

Year	Point Forecast	80% CI		95% CI	
		Low	High	Low	High
2023	9,056.84	8,264.61	9,849.07	7,845.22	10,268.46
2024	10,297.99	8,652.53	11,943.45	7,781.47	12,814.51
2025	11,316.25	8,745.28	13,887.21	7,384.30	15,248.19

Note: Low and High indicates the confidence interval limits

3.2.8. Constraints identification through Garrett ranking

The identification of region-specific constraints is essential for developing targeted mitigation strategies to promote aquaculture activities. The constraints identified using the Garrett ranking in pond and cage cultures varied across regions. The availability of quality seeds was the primary technical constraint, in addition to the availability of stockable-size fingerlings, formulated feed, and health and environmental issues. The cost of seed and feed and lack of credit were the major economic constraints, while unstable local market demand and high price spread were also reported by farmers (Table 12). Previous studies have also identified the high cost of feed, poor-quality seeds (Jeeva et al., 2022), and lack of credit and insurance (Aswathy and Imelda, 2020) as the primary constraints in mariculture. Overall, the sector faces poor input supply logistics as a critical administrative constraint, along with a lack of adequate technical supervision and guidance across the culture systems. Therefore, concerted efforts by developmental, promotional, and research organizations to establish more hatcheries would ensure a timely supply of adequate amounts of quality seeds and facilitate the development of low-cost formulated feed, along with expanding domestic and global market opportunities.

Table 12. Garret ranking on perceived constraints in seabass culture.

S no	Constraint Analysis	Pond culture		Cage culture		
		Andhra Pradesh	West Bengal	Kerala	Tamil Nadu	Karnataka
Technical constraints						
1.	Non-availability of quality seed	1	1	2	1	1
2.	Selling of fish	10	7	12	5	2
3.	Non-availability of formulated feed	2	13	6	3	12
4.	Skilled labor shortage	8	9	10	10	14
5.	Electricity	6	12	11	11	15
6.	Mortality	3	3	1	2	13

S no	Constraint Analysis	Pond culture		Cage culture		
		Andhra Pradesh	West Bengal	Kerala	Tamil Nadu	Karnataka
7.	Disease infection	4	4	3	6	8
8.	Lack of knowledge	7	5	13	13	5
9.	Lack of availability of good quality water	11	10	9	9	10
10.	Perishable commodity resulting in losses	13	11	14	14	4
11.	Poaching	5	2	4	4	6
12.	Post-harvest management	12	8	15	15	11
13.	Lack of transportation facilities	9	6	8	12	7
14.	Storage facilities	14	14	5	8	9
Economic constraints						
1	Unstable price of the product	8	7	3	4	1
2	High cost of seed (including transportation)	2	2	4	5	2
3	High cost of feed	1	8	1	1	9
4	Lack of money for constructing pond	6	3	9	9	6
5	Lack of credit	5	1	5	7	5
6	Lack of insurance	10	10	8	10	8
7	Cost of electricity	9	4	10	8	10
8	High labor charge	7	5	7	6	7
9	Exploitation by commission agents	3	6	2	2	3
10	Unstable local demand	4	9	6	3	4
Administrative constraints						
1	Lack of timely & adequate supply of fingerlings	1	3	1	2	1
2	Lack of frequent technical supervision and guidance	3	1	4	4	4
3	Untimely supply of inputs & other materials	2	4	3	1	2
4	Lack of communication regarding the services & other facilities available for fish farming	7	5	7	7	3
5	Location of fish collection centers at distant places	6	7	6	3	7
6	Lack of demonstration and training on recommended practices	4	2	2	5	5
7	Lack of facilities for testing soil, seed and water quality.	5	6	5	6	6

3.3. SWOT Analysis

SWOT analysis of seabass aquaculture indicates the immediate interventions required for the sustainable development of the sector (Ravisankar et al., 2010 FAO, 2020b). The availability of technology for year-round breeding and seed production, in addition to the development of functional feed for various growth stages, such as broodstock, nursery, pre-grow-out, and grow-out feed denotes the major strength. Employing the available qualified young professionals across potential coastal and inland saline water bodies would ensure tapping of domestic and international market opportunities. The cost and availability of quality seed and feed and the long distance of transportation are the major identified weaknesses that need to be addressed through research inputs for the development of policy interventions. Additionally, providing institutional credit and risk mitigation through insurance would help achieve targeted production and ensure the economic sustainability of the sector (Table 13).

The integrated seabass culture system practiced in Indian seabass farming ensures phase-wise growth at different facilities, ensuring year-round production generating employment and revenue for communities, thus transforming seabass into a major aquaculture species supporting livelihoods. The factors identified in the constraint analysis were used to recommend targeted strategies and policy interventions to aid sustainable development of this emerging aquaculture system.

Table 13. SWOT analysis of Indian seabass production

Strength	Weakness
Availability of scientific breeding technology	Inadequate availability of weaned seed
Higher consumer preference	Less awareness among farmers about using formulated feed
Establishment of Hatcheries	High cost of seed and feed (additional transport cost)
Zero conflict water resource	Health and environmental issues
Availability of species-specific feed	Lack of credit and insurance
The commitment of promotional agencies	Exploitation by commission agents
Livelihood improvement	Unstable local demand
	Lack of scientific farming know-how
	Dependence on forage fish
Opportunities	**Threat**
Availability of potential brackish water area	Failure to meet production capacity
Huge seed demand	High price spread
Scope for expansion of hatcheries and feed mill capacity	Unsustainable farming practices
Promotion through Farmers Producers Organizations (FPO)	Increased non-institutional credit

Strength	Weakness
Scope for diversification in brackish water aquaculture	Underutilization of the potential
Large domestic and international market	Live fish feed as disease carriers
Scope for inclusion in national flagship programs	
Increasing employment opportunities	

3.4. Scaling-up Seabass Culture: Future Prospects and Requirements

Given the above strengths, weaknesses, opportunities, and threats, some potential strategies and actions required to scale up seabass culture in India are outlined below:

1. Expansion of Hatchery Infrastructure
   - Increasing the number of fish seed hatcheries to ensure copious seed availability.
   - Promoting private sector hatcheries through financial assistance from the government.
2. Feed Production and Supply Chain
   - Encouraging feed mills to produce exclusive feeds for seabass.
   - Promoting research on alternative crude protein and crude fat sources with cost-effective formulations.
3. Market Development and Value Chain Enhancement
   - Developing domestic marketing strategies for seabass.
   - Strengthening cold chain and transportation infrastructure.
   - Promoting branding and certification for better consumer acceptance.
4. Policy and Financial Support
   - Popularizing government schemes to support seabass farming.
   - Encouraging public-private partnerships for domestic marketing.
   - Facilitating access to credit and insurance for fish farmers.
5. Capacity Building and Technology Transfer
   - Conducting training programs for fish farmers on best management practices.
   - Establishing demonstration farms for knowledge dissemination.
   - Enhancing digital advisory services for real-time technical support.

4. Conclusions

This study provides a comprehensive analysis of the current status, farming systems, production economics, efficiency, challenges, and prospects of Asian seabass aquaculture in India. Advancements in seed production and feeding methodologies can enhance survival rates, growth rates, and yields across nurseries, pre-grow-out ponds, and grow-out culture systems. Overall viability is constrained by recurring expenses, such as seed and feed costs, in addition to inadequate institutional support. Annual seabass production forecasts predict continued output growth in subsequent years. However, targeted strategies are imperative to facilitate large-scale sustainable expansion. Recommendations include upgrading hatchery and feed infrastructure, building capacity among farmers, facilitating access to credit, mitigating risk through insurance, and securing market linkages. The study provides robust insights into the enhancement of evolving cultural practices and the realization of the sector's full potential. This proposed approach allows for extrapolation to other aquaculture systems and geographical regions that face similar opportunities and limitations.

Asian seabass production systems demonstrated that the implementation of efficient, integrated multi-tier production facilitates consistent year-round production. The economic analysis indicates predominantly positive returns, although profitability varies due to location-specific productivity, costs, and prices. Nevertheless, identified constraints in obtaining a timely supply of adequate quantities of quality seed and feed could be addressed through the establishment of additional hatcheries and the development of cost-effective formulated feed, along with the expansion of domestic and global market opportunities. By addressing these key challenges through appropriate technological, policy, and marketing interventions, Asian seabass aquaculture has the potential to significantly enhance production and return, thereby ensuring livelihood security.

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Annexure 1. Time-series forecasting methods for seabass production.

Forecasting method	AIC	AICc	BIC	RMSE	MAE	MPE	MAPE	MASE	Parameter Estimates			
Naïve	-	-	-	599.60	522	24.30	24.30	1.0	-			
Simple Exponential Smoothing	204.60	207.27	206.30	576.12	481.92	-Inf	Inf	0.92	Smoothing parameters: alpha = 0.999		Initial states: l = 0.43	
Holt's method	188.43	197.00	191.25	265.147	221.844	NaN	Inf	0.42	Smoothing parameters: alpha = 1e-04 beta = 1e-04		Initial states: l = -670.1965 b = 554.4798	
ARIMA (0,1,0)	189.57	189.97	190.05	576.08	481.85	24.30	24.30	0.92	Ar1	Ar2	Ma1	Ma2
									-	-	-	-
ARIMA (1,1,0)	183.53	184.87	184.50	401.30	264.88	12.38	14.77	0.50	0.7286 (0.2399)	-	-	-
ARIMA (0,1,1)	187.09	188.42	188.06	471.00	343.49	17.62	17.95	0.65	-	-	0.5489 (0.2616)	-
ARIMA (2,1,0)	183.20	186.23	184.66	357.11	236.19	10.71	14.57	0.45	0.3254 (0.2691)	0.4983 (0.2928)	-	-
ARIMA (2,1,1)	182.72	188.44	184.66	288.08	214.34	8.06	12.25	0.41	0.7783 (0.3366)	0.2216 (0.3368)	-0.9767 (0.1444)	-
ARIMA (2,1,2)	184.73	194.73	187.16	289.21	214.60	8.08	12.28	0.41	0.7282 (1.0196)	0.2717 (1.0195)	-0.9235 (1.0585)	-0.045 (1.027)