Chapter-3

Small-Scale Mariculture in India: Status, Impact and Potential

Shinoj Parappurathu, Johnson Belevendran, Muktha Menon, Swathi Lekshmi PS, Anuraj Anirudhan, Divu Damodaran, Ramachandran C, Shelton Padua, Geetha R, Vinuja SV, Baiju KK, Preethi VP, Suresh VVR, Gopalakrishnan A and Rajni Jain

1. Background

Capture fisheries, finfish, and bivalve mariculture constitute the primary components of the blue economy. These sectors contribute approximately 17% of global edible meat production (Costello et al., 2020). By 2050, the intensification of mariculture (36-74% increase in yield) facilitated by technological advancements and policy reforms can enhance food production from the sea by 21-44 million tons (Edwards et al., 2019; Costello et al., 2020, Divu et al., 2020).

The Government of India has emphasized mariculture as a source for augmenting marine fish production and sustaining coastal livelihoods by addressing the institutional and commercial requirements of this emerging sector (GoI, 2017). Mariculture is predominantly practiced in shallow marine and internal waters and comprises capture and hatchery-based fin-fish and shell-fish culture, which includes cage culture (in the open sea and internal waters), bivalve culture, aquaculture systems such as seaweed culture, pearl and oyster culture, and ornamental fish culture. However, the current mariculture production in India is estimated to be negligible at less than 0.1 million tons against a potential of 4-8 million tons (Jena et al., 2022).

In India, mariculture is predominantly a small-scale enterprise. However, with continuous technological advancements and their adoption by small-scale fishing communities, there is potential for sustainable intensification (SI) of farming operations. Promising ventures for potential expansion include open sea and 'coastal water' cage farming of finfish and shellfish, cultivation of seaweed, and Integrated Multi-Trophic Aquaculture (IMTA), among others (Gopalakrishnan et al., 2017). The Government of India has recently initiated ambitious programs to support such farming endeavors (NFDB, 2018). However, their success is largely dependent on a comprehensive understanding of the suitability of each aforementioned technology in relation to the specific socioeconomic and demographic characteristics of the farming communities involved, as well as the prevailing status of the markets and institutions (Little et al., 2013; Bostock et al., 2010).

This chapter presents a comprehensive economic assessment of the selected mariculture enterprises in India[1].

2. Mariculture in India

2.1. Status

The earliest documented attempt towards the culture of marine fish species in India can be traced to the farming of milkfish, *Chanos chanos* in 1958-59 (Gopakumar et al., 2007). Subsequently, in the 1970s, experimental trials were conducted to standardize the culture of green mussels (*Perna viridis*) and brown mussels (*P. indica*) using rack, long-line, and raft methodologies (Appukuttan and Alagarswami, 1980; Kuriakose, 1980). The cultivation of pearl oysters (*Pinctada fucata* and *P. margaritifera*) was also investigated along the coast of Tamil Nadu (Alagarswamy, 1974). Other mariculture attempts include seaweed farming experiments initiated in 1964 in Gujarat (Thivy, 1964), followed by experimental trials and commercial exploitation along the southeast coast of Tamil Nadu for agar and algin production (Silas and Kalimuthu, 1987).

Initiatives in open-sea cage culture were taken in the mid-2000s with the Asian seabass (*Lates calcarifer*), which led to locally adapted innovations in the design and fabrication of cages and mooring systems, standardized guidelines, and farming practices, as well as the development of breeding, larval production, and grow-out technologies for several prioritized marine finfish species (Rao et al., 2013; Ayyappan et al., 2015). So far, the ICAR-Central Marine Fisheries Research Institute (CMFRI), India, has standardized techniques for breeding and seed production, including nursery protocols for Cobia (*Rachycentron canadum*) Orange-spotted grouper (*Epinephelus coioides*), Silver pompano (*Trachinotus blochii*), Indian pompano (*T. mookalee*), Pink-ear sea bream (*Lethrinus lentjan*), banded grunter (*Pomadasys furcatus*), John's snapper (*Lutjanus johnii*), Vermiculated spine foot (*Siganus vermiculatus*) and picnic seabream (*Acanthopagrus berda*) (Gopalakrishnan et al., 2019). The culture technology for Asian seabass in brackishwater has been standardized by the ICAR-Central Institute of Brackishwater Aquaculture (CIBA) (Arasu et al., 2009). ICAR-CMFRI has prioritized 76 finfish and shellfish species that could be targeted for the future expansion of mariculture (Ranjan et al., 2017). Most of these technologies have either been transferred or are at various stages of farm-level demonstration. The major candidate species

[1] Some sections of this chapter are featured in Parappurathu et al. (2023).

used in coastal water cage farming include Asian seabass, Silver pompano, Indian pompano, mullets (*Mugil cephalus*), milkfish (*C. chanos*), Mangrove red snapper (*Lutjanus argentimaculatus*), pearl spot (*Etroplus suratensis*), and Genetically Improved Farmed Tilapia (GIFT) (*Oreochromis niloticus*). Recent studies have shown that cage farming is economically viable, and spreading rapidly along the coasts (Aswathy et al., 2020; Jena et al., 2022).

Seaweed farming has been identified as a diversified livelihood option for coastal fishers in India. However, the enabling factors for significant commercial expansion and holistic development of allied industries have yet to materialize (Johnson et al., 2017; 2020). Previous studies (Kaliaperumal and Kalimuthu, 1997; Rao and Mantri, 2006) have identified several commercially important seaweed species, including red algae species such as *Gracilaria edulis, Gelidiella acerosa, and Kappaphycus alvarezii* and brown algae species such as *Sargassum wightii, Turbinaria conoides,* and *Cystoseira* spp. Several techniques using floating rafts, net tubes, longlines, and fin-fish-stocked cage-based IMTA systems have been standardized for seaweed culture. Recent literature indicates that farming of seaweed species, including *K. alvarezii*, *G. acerosa*, and *Gracilaria* spp. is economically profitable, and is therefore suitable for commercialization (Mantri et al., 2022).

Moreover, the demand for seaweeds has increased because of their utilization in the production of secondary bioactive metabolite-based nutraceuticals, plant growth promoters, and fertilizers (Chakraborty et al., 2018). Johnson et al. (2020) identified a potential area of 23,970 hectares suitable for seaweed cultivation along India's shallow coastal waters. Currently, seaweed farming is practiced on a limited scale along the Palk Bay areas of Tamil Nadu and is supported by carrageenan, agar, and seaweed-based fertilizer industries located in the vicinity. Previously, the cultivation of K. alvarezii experienced a period of rapid growth during 2000-2013 when local fishers along the coasts of Tamil Nadu, Gujarat, and Odisha entered into a contract farming arrangement with PepsiCo India Holdings Ltd., followed by Aqua Agri Processing Pvt. Ltd. for carrageenan production. However, this endeavor did not succeed because of numerous biophysical and economic constraints (Krishnan and Narayanakumar, 2013). Nevertheless, seaweed farming is re-entering a renewed phase, owing to substantial policy emphasis and technological and logistical advancements.

Integrated Multi-Trophic Aquaculture (IMTA) is another novel practice that has been gaining momentum because of its bio-mitigation potential, complementary ecosystem functions, and economic potential (Chopin et al., 2008). Integrated trials carried out by ICAR-CMFRI involving cobia in marine cages and *K. alvarezii* in floating rafts set around the cage in Palk Bay areas have shown encouraging results (Johnson et al., 2021). Similar trials involving different combinations of mullets (*M. cephalus and Liza parsia*), milkfish (*C. chanos*), pearl spot (*E. suratensis*), and shrimp (*Penaeus monodon, P. indicus*) as feed species, together with oysters (*Crassostrea cuttackensis, C. madrasensis*) and seaweed (*Enteromorpha* spp.) as extractive species, have found viable aquaculture options in brackishwater ecosystems of Sundarban in West Bengal and Sindhudurg in Maharashtra (Balasubramanian et al., 2018). Efforts to popularize IMTA with the integration of Silver Pompano, Asian Seabass, and Green Mussel in the Udupi and Uttara Kannada in Karnataka have been highly successful (Anuraj et al., 2022). Recognizing this potential, fishermen from Palk Bay and other parts of the southwest coast of India have recently started practicing IMTA-based farming.

2.2. Institutional and Policy Support

The research and development activities in mariculture in India are primarily conducted by public institutions and agencies. Research on the development of culture technologies and associated areas has been conducted by ICAR-CMFRI, Kochi, ICAR-Central Institute of Brackishwater Aquaculture (CIBA), Chennai, Central Salt and Marine Chemicals Research Institute (CSIR-CSMCRI), Bhavnagar, National Centre for Sustainable Coastal Management (NCSCM), and National Institute of Ocean Technology (NIOT), Chennai.

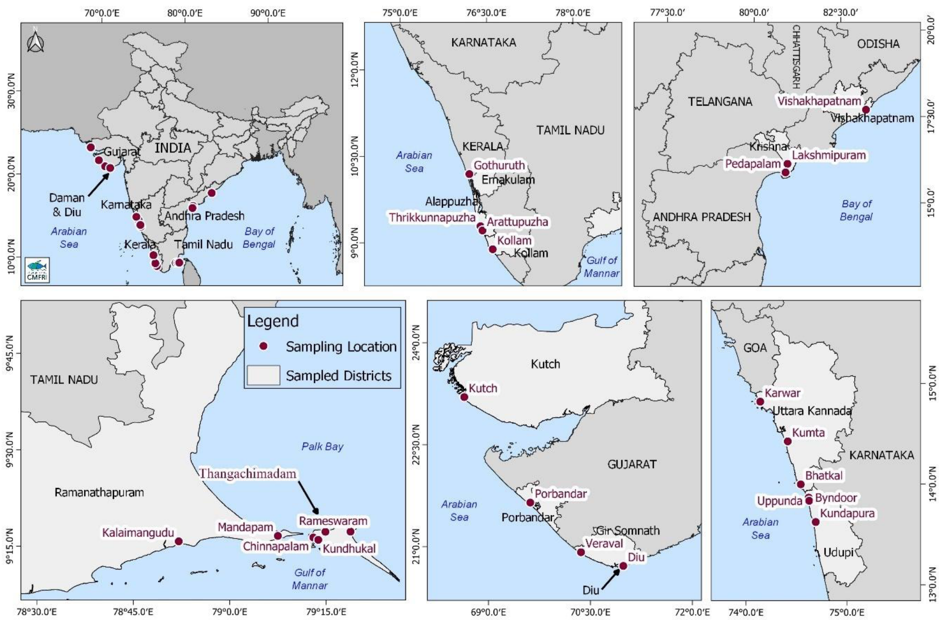
Initially, research endeavors were isolated and implemented in a project-based manner by individual institutes and universities. Recently, coordinated research has been established through network projects such as the 'All India Network Project on Mariculture' by the Indian Council of Agricultural Research (ICAR) and other inter-institutional collaborative research efforts involving NCSCM, CSIR-CSMCRI, and State Universities.

Moreover, developmental initiatives encompassing training, funding, and logistical support provided by government parastatals, such as the National Fisheries Development Board (NFDB), Hyderabad, and the Marine Products Export Development Authority (MPEDA), Kochi, have contributed significantly to the promotion of mariculture. Currently, the majority of these developmental programs are supported through budgetary allocations under the Pradhan Mantri Matsya Sampada Yojana (PMMSY). In 2019, the NFDB prepared a draft National Mariculture Policy that identified key areas for development and associated policy imperatives. Subsequently, this draft was incorporated into the 'National Fisheries Policy 2020,' which is currently awaiting notification by the Government of India.

Furthermore, various maritime state governments are in the process of establishing distinct state-level policies to facilitate mariculture at the grassroots level. The Government of Goa enacted the 'Goa State Mariculture Policy 2020' in June 2022, which represents the first such policy in the country. Under this policy, an open sea cage farm was established in Candolim, North Goa, a pioneering initiative, with technical guidance from the Karwar Regional Station of the ICAR-CMFRI (Anonymous, 2022).

In the following sections, we provide evidence on the adoption of different mariculture technologies and their impacts and identify indicators of their sustainability.

Fig. 1. Study locations



3. Data and Methods

3.1. Data

This investigation was motivated by the necessity to document and analyze the status and impact of mariculture enterprises in the coastal regions of India, as well as the potential for their sustainable intensification. Consequently, the study locations encompassed the emerging mariculture hotspots: Tamil Nadu and Andhra Pradesh along the east coast; Kerala, Karnataka, and Gujarat, on the west coast of India, and the Union Territory (UT) of Diu enveloped by Gujarat. The specific locations are illustrated in Fig.1, and the coverage of various mariculture enterprises is presented in Annexure A1.

The selection of locations for primary surveys was made based on predetermined criteria that include: (i) a substantial presence of operational mariculture units practicing one or more of the selected enterprises covered in the study, (ii) the presence of auxiliary enterprises such as seed production centers/hatcheries, fish markets, processing units, etc. in proximate locations, and (iii) established linkages of the entrepreneurs with research and development institutions and agencies involved in marine/coastal aquaculture. These criteria were implemented to ensure that the multiple dimensions associated with viable and sustainable mariculture, including social and institutional preconditions, and forward and backward integration vis-à-vis fish input and product value chain nodes, could be adequately examined.

The first phase of the survey involved in-depth discussions with the scientists and practitioners engaged in mariculture regarding the details of farming activities being carried out in the locality. Subsequently, a set of semi-structured questionnaires was developed for each enterprise, which were pretested and fine-tuned to location-specific contexts. The survey findings were validated and triangulated with key informants and experts.

The selected mariculture enterprises included (i) open sea cage farming, (ii) coastal water cage farming, (iii) IMTA, and (iv) seaweed farming. The surveys were administered by randomly selecting farm units in purposively selected coastal regions where mariculture has recently been established as an alternative livelihood option. Care was taken to capture the diversity of farmed species and culture practices across the sample farms in a given location by following the broad principles of stratification (although no formal stratified sampling methods were adopted). The respondents were either owner-farmers or farm managers responsible for the daily activities of the farm units.

To assess the economic impact of cage farming (other mariculture enterprises were not considered), it was deemed necessary to collect data from comparable households that do not currently engage in cage farming (to serve as counterfactual units). These non-adopter farm households were selected to ensure that their household, demographic, and socioeconomic characteristics were similar or comparable to those of the adopter households in each locality. To ensure comparability, such households were selected from locations in close proximity to the water bodies where culture activities were conducted, such that given an opportunity, they possessed the circumstantial capacity to initiate mariculture activities.

Specific details of the sample units covered in each identified location are shown in Annexure A1 and A2 presents a separate sampling framework for data collection, covering adopters and non-adopters[2]. Secondary data were gathered from various published and unpublished sources to facilitate an objective assessment of mariculture potential.

2 These two surveys were carried out separately with some time lag, but there are overlaps for adopters as sample units.

3.2. Analytical Framework

3.2.1. Heckman selection model

It is imperative to understand the primary factors that influence income variability in cage farming. However, a direct assessment based solely on a sample of cage farming adopters may result in sample selection bias. To mitigate this bias, the Heckman selection model was employed, wherein the probability of a unit being selected was determined using a selection equation (Heckman, 1979). Furthermore, it enables: (i) prediction of producer participation in cage farming and (ii) determination of the factors affecting net income from production for those with positive production. The behavior of a representative producer is represented by the following equation:

$$y_i = x_i{}'\beta + \varepsilon_i \qquad (1)$$

Where y_i is the amount or value of output for producer i, and x_i is a vector of explanatory variables. β is a vector of unknown parameters, and ε_i is an error term. The selection equation for cage farming was as follows:

$$z_i{}^* = w_i{}'\gamma + u_i \qquad (2)$$

$$z_i = \begin{Bmatrix} 1 & if\ z_i{}^* \geq 0 \\ 0 & otherwise \end{Bmatrix} \qquad (3)$$

Where $z_i = 1$ for participants in cage culture (i.e., y_i is observed), and zero otherwise; w_i is a vector of explanatory variables; and u_i is an error term. To analyze the factors determining net income from cage farming, the following Heckit model for cross-sectional data was used:

$$E(y_i|w_i, z_i = 1) = x_i{}'\beta + \beta_\lambda \lambda\,(w_i{}'\gamma) \quad (4)$$

Where $E(y_i|.)$ is the expected mean net income, conditional on selected sample, and the set of explanatory variables included in w_i. This expression can be written as a reduced-form equation:

$$y_i = x_i{}'\beta + \beta_\lambda \lambda\,(w_i{}'\hat{\gamma}) + \varsigma_i \qquad (5)$$

Where x_i is a vector of explanatory variables, $\lambda\,(w_i{}'\hat{\gamma})$ is the inverse Mills ratio, and β and β_λ are unknown parameters.

3.2.2. Propensity score matching

Propensity score matching (PSM) is a quasi-experimental technique in which the impact of an intervention (i.e., cage farming) is assessed by comparing how outcomes differ for adopters in relation to observationally similar non-adopters. PSM uses information from a pool of units that do not participate in the intervention to identify what would have happened to the participants in the absence of intervention (Rosenbaum and Rubin, 1983). The above method seeks to assess the impact of a treatment, 'd' for an individual 'i' by estimating the difference between the potential outcome in the case of treatment (Y_{1i}) and potential outcome in the absence of the treatment (Y_{0i}). The impact of the program denoted by 'δ_i' is expressed as:

$$\delta_i = Y_{1i} - Y_{0i} \qquad \text{...... (1)}$$

The mean impact of the program was obtained by averaging δ across all the treated individuals. This parameter is known as the average treatment effect on the treated (ATT).

$$\hat{\delta} = E(Y_{1i}|X_{i,} d_i = 1) - E(Y_{0i}|X_{i,} d_i = 1) \qquad \text{....... (2)}$$

Where, X_i is a set of observable characteristics of the individuals and *E (...)* denotes expected value.

Here, the term $E(Y_{0i}|X_{i,} d_i = 1)$ is the average outcome that the treated individuals would have obtained in the absence of treatment (*counterfactual*), which is unobserved. However, it is possible to obtain the term $E(Y_{0i}|X_{i,} d_i = 0)$, which is the value of Y_0 for the untreated individuals. Therefore, we can calculate:

$$\Delta = E(Y_{1i}|X_{i,} d_i = 1) - E(Y_{0i}|X_{i,} d_i = 0) \quad \text{....... (3)}$$

Re-arranging Equation (3) can establish that, $\Delta = ATT + SB$, where SB is the selection bias, defined as the difference between the unobserved *counterfactual* for the treated individuals and the observed outcome for the treated individuals. If SB = 0, ATT can be estimated by taking the mean observed outcomes for the treated and untreated samples. In the literature, there is a consensus that by randomly assigning units to treatment and control groups, selection bias can be minimized. However, participation in most socio-economic programs being non-random and conditional based on X, an alternative approach called 'matching' can be followed that helps in obtaining unbiased estimator of ATT. Matching essentially helps in pairing a participant unit with an observationally similar non-participant unit so that the difference in their outcomes is as good as the difference between the treatment outcome and its *counterfactual*. With no underlying selection bias, this difference can be interpreted as an effect of the programme (Smith and Todd, 2005).

PSM matches the treated and untreated units based on the estimated propensity score, that is, the probability that a unit in the combined sample of the treated and untreated units receives the treatment, given a set of observable characteristics. The propensity score is generally estimated by fitting a probit or logit equation, with participation in the program as the dichotomous dependent variable (d = 1 if participant; d = 0 if not). All observed characteristics that the researcher found to be determining factors for participation in the program, thereby impacting the outcome variable Y, were included as explanatory variables. Several alternative algorithms, such as *nearest neighbor matching*, *radius matching, stratification matching,* and *kernel matching,* were used to match the treated units with those of the control. After matching, the ATT and the associated standard errors were estimated and compared to assess the impact of the program.

A probit model was fitted with cage farming adoption as the dependent variable and several household-specific demographic and socioeconomic determinants as explanatory variables. The estimation of the probit model and subsequent computations on propensity scores were carried out using the 'pscore.ado'[3] module in the STATA software. Subsequently, ATT estimates based on *the nearest-neighbor matching and stratification methods* were obtained and presented.

3.2.3. PCI framework for sustainable intensification

The concept of sustainable intensification (SI) aims to achieve at least one of the following objectives: (i) improved production and resource use efficiency with respect to land, water, feed, and energy; (2) enhanced environmental benefits; (3) strengthened economic viability and farmers' resilience; and (4) improved social acceptance and equality, while not compromising others (FAO, 2016). The concept originated in African smallholder agriculture (Pretty, 1997) and primarily addresses the production of increased output with reduced input, while minimizing negative environmental impacts and optimizing societal benefits (Little et al., 2018).

To establish a linkage between various dimensions of sustainability, different sets of farm-level indicators were constructed by broadly following the Principles-Criteria-Indicators (PCI) framework (Rey-Valette et al., 2008, 2010). PCI establishes a cascading relationship between principles (which express the values and issues of sustainability), criteria (variables that are most appropriate for expressing these principles), and indicators (variables to be measured). However, in this study, context-specific deviations were made to suit location/enterprise-specific realities without compromising the core ideas of the approach. Annexure Table A3 presents the key dimensions, criteria, and indicators used to assess the present level of economic viability, environmental sustainability, and social acceptability of mariculture enterprises, in addition to their future orientation for SI.

[3] This module was developed by Becker and Ichino (2002) and is available for download at http://sobecker.userweb.mwn.de/pscore.html.

4. Results and Discussion

4.1. Farming profile of mariculture units

The majority of open-sea cage farms were operated by small-scale fishers possessing no more than two units with one crop per annum. As an exception, a limited number of farmers in Gujarat, Kerala, and Andhra Pradesh owned and operated 4-10 cages. The farm units were situated in clusters within suitable areas characterized by low tidal activity, predominantly within a one-kilometer radius from the shore, where the depth ranged from 10 to 15 m.

Sea cage farming in Tamil Nadu, Andhra Pradesh, and Gujarat was primarily practiced in circular marine cages constructed of high-density polyethylene (HDPE) or galvanized iron (GI), measuring 6 meters in diameter and 4 meters in depth (113 m^3). These cages were initially designed and disseminated by ICAR-CMFRI in the late 2000s, and subsequently refined. All sample farms in Tamil Nadu cultivated Asian Seabass sourced from the wild for a duration of 7-8 months, whereas those in Visakhapatnam of Andhra Pradesh state cultivated Indian pompano and Orange-spotted grouper sourced from hatcheries for an 11-month culture period. The spiny lobster (*Panulirus homarus*) was cultivated for a comparatively short duration of 4-6 months along the coasts of Gujarat and Diu.

Seeds required for cage culture were either collected from the wild or obtained directly from private and public hatcheries. Public hatcheries were primarily operated by research institutions, such as ICAR-CMFRI, ICAR-CIBA, Rajiv Gandhi Centre for Aquaculture (RGCA), and other state-funded agencies. Government agencies, such as the NFDB, through their network of Aqua One Centers and State-level aquaculture development agencies, also provided subsidized seeds sourced from certified hatcheries. The majority of farmers implemented a mixed feeding regime, that is, formulated pellet feed in the initial phases of the crop, with raw fish gradually substituted in advanced growth stages. Yields varied significantly depending on the location and the species, with the highest being 16 kg/m^3 in the case Indian Pompano in Vishakhapatnam (Table 1).

In comparison to open-sea cages, coastal water cages are characterized by smaller dimensions and a rectangular configuration, typically constructed from Galvanized Iron (GI). The volumetric capacity of these structures varied but generally did not exceed 75 m^3. Similar to sea cage farmers, coastal water cage farmers operate on a small scale, managing 1-2 units with a production cycle of 6-12 months. These aquaculture facilities were predominantly situated in internal backwaters or estuaries in close proximity to the shore (15-200 m), where water depths ranged from to 2-10 m. The ownership and management of these farms relied primarily on domestic labor. The Asian seabass was the predominant species cultivated across all locations, although other species, such as red snapper, silver pompano, and Indian pompano, were also reared. In certain localities, brackish water species, including pearl spots and mullets, are cultivated alongside the aforementioned species.

The formulated pellet feed was used to feed hatchery-based Asian seabass in Karnataka and Kerala, Indian pompano in Kerala, and silver pompano in Andhra Pradesh. In many cases, a combination of raw fish and pellet feed has been used depending on the growth phase of the crop at varying feeding rates. As in the case of marine cage farms, crop yields varied widely, ranging from 8 to 16 kg/m^3 across locations and species. The highest yield (18.3 kg/m^3 on average) was reported by farmers practicing polyculture of Asian seabass and red snapper for an extended crop duration of 8-18 months in Karnataka (Table 1).

Table 1. General features of sample farms practicing mariculture in the selected coastal regions of India

Feature		Sample locations		
I. Open sea cage farming				
		Tamil Nadu	**Andhra Pradesh**	**Gujarat**
Type of the cage		Circular HDPE cage (n = 20)	Circular HDPE cages (n = 7)	Circular GI & HDPE cages (n = 14);
Average number of units/ farm (owned by a person/ group)		1.3	10#	2.7
Size of the unit (DiaxD) in m		6x4	6x4	6x6 (HDPE); 5x4.5 (GI)
Distance from the shore (m)		1000	500-750	500-800
Depth of water (m)		5-6	10	8-15
Major species farmed		Asian seabass (ASB)	Indian pompano (IP), Orange spotted grouper (OSG)	Lobster
Crop duration (months)	Species 1:	7-8	IP: 11	4-6
	Species 2:	-	OSG: 11	-
Feed type (raw fish/locally formulated/ concentrate/ pellet)	Species 1:	Trash fish	IP: Trash fish, Formulated pellet feed	Trash fish
	Species 2:	-	OSG: Raw fish	-
Average Yield (kg/m^3/unit)	Species 1:	10.7 (SD: 1.5, n = 20)	IP: 16.0 (SD: 0.4, n = 4)	Lobster: 3.7 (SD: 0.2, n = 12)
	Species 2:	-	OSG: 13.3 (SD: 0.2, n = 3)	-

Feature		Sample locations		
II. Coastal water cage farming				
		Karnataka	**Kerala**	**Andhra Pradesh**
Type of the cage		Rectangular GI (n = 34)	Rectangular GI cage (n = 30)	Rectangular GI cage (n = 10)
Average number of units/ farm (owned by a person/ group)		1.5	1.1	1.6
Size of the unit (LxBxD) in m		6x3x2 (n = 21); 4x4x3 (n = 7); other (n = 6)	4x4x3 (27); 6x6x4 (3)	5x5x3
Distance from the shore (m)		10-200	10-100	15-100
Depth of water (m)		3-6	2-5	4-10
Major species farmed		Asian seabass (ASB) Red snapper (RS)	ASB, Pearl spot (PS)	ASB, Indian Pompano (IP)
Crop duration (months)	Species 1:	ASB: 8-12	ASB: 8-12	ASB: 6-7
	Species 2:	RS: 8-18	PS: 8-12	IP: 5-7
Feed type (raw fish/locally formulated/ concentrate/ pellet)	Species 1:	ASB: Raw fish, Formulated pellet feed	ASB: Formulated pellet feed	ASB: Trash fish
	Species 2:	RS: Trash fish	PS: Formulated pellet feed	IP: Formulated pellet feed
Average Yield (kg/m^3/unit)	Species 1:	ASB: 9.2 (SD: 4.8; n = 21)	ASB: 16.6 (1.6, n = 16)	ASB: 6.3 (SD: 3.5; n = 4)
	Species 2:	RS: 8.9 (SD: 2.6; n = 7)	PS: 5.9 (3.5, n = 14)	IP: 8.3 (SD: 3.3; n = 6)
	Poly-culture:	ASB + RS: 18.3 (SD: 5.8; n = 6)	-	-
III. Integrated Multi-Trophic Aquaculture (IMTA)				
		Tamil Nadu	**Karnataka**	
Type of the unit	Fish/ shellfish cage	Circular (HDPE/GI) cages (n = 10)	Rectangular wooden cages (n = 4)	
	Mussel/ seaweed raft	Rectangular wooden rafts	Rectangular wooden rafts	
Average number of units/farm	IMTA	1.1	1.2	
Size of the unit (LxBxD)/ (DiaxD) in m	Fish/ shellfish cage	6x6	6x4x4 (rectangular)	
	Mussel/ seaweed raft	3.6x3.6	6x6	
Distance from the shore (m)		1000	10-300	

Feature		Sample locations	
Depth of water (m)		5-6	4-9
Major species farmed	Fed species	Cobia	Asian seabass (ASB); Red snapper (RS)
	Extractive species	Red seaweed (*Kappaphycus alvarezii*) (KA)	Green mussel (GM)
Crop duration (months)	Fed species:	Cobia: 7-8	ASB & RS: 8-12
	Extractive species	KA: 45 (days), (4 cycles/year)	GM: 5-7
Feed type (raw fish/locally formulated/ concentrate/ pellet)	Fed species:	Cobia: Trash fish	ASB& RS: Trash fish
Average Yield (kg/m³/unit)	Fed species:	Cobia: 11.4 (SD: 1.1, n = 10)	ASB: 4.0 (SD: 0.2, n = 2); RS: 6.9 (SD: 3.93, n = 2)
	Extractive species	KA: 1254 (kg wet weight/raft for 4 cycles) (SD: 50.3, n = 10 units of 16 rafts each)	GM: 7.8 kg/rope (SD: 2.5, n = 4)

*Note: #Farming was carried out by a fisheries cooperative society and cages were established in clusters, each carrying a battery of 10. *Feeding rate is expressed as the average quantity fed through the crop duration; it might differ across growth phases, all of which pertain to the most recent cycle of the crop.*

The IMTA farms were of two types: (i) open sea cage farming of cobia integrated with red seaweed (*K. alvarezii*) in the Mandapam region of Tamil Nadu state and (ii) coastal water cage farming of Asian seabass and red snapper integrated with green mussel in the Byndoor region of Karnataka. In the former case, each unit consisted of one HDPE circular cage encircled by approximately 16 nearby seaweed rafts. The units were located approximately one km from the shore, at a water depth of 5-6 meters. The cages were stocked with cobia seeds mainly sourced from hatcheries. Seaweeds were raised in rectangular rafts in four cycles of 45 days each during a cropping season. Respondents practicing this system reported having realized an average yield of 11.4 kg/m^3 of cobia and 1254 kg of *K. alvarezii* per raft. The coastal water IMTA units were located very close to the shore and each unit consisted of one rectangular cage surrounded by 1-2 green mussel rafts. Each raft carried 50-100 seeded ropes suspended in the water body. Crop duration ranged from 8 to 12 months for the fed species and 5-7 months for the extractive species (green mussel). At the end of the harvest season, the average fish yield realized by the sample farmers was 4.0 kg/m^3 for Asian seabass and 6.9 kg/m^3 for red snapper. The average green mussel yield recorded was 7.8 kg/rope with a standard deviation of 2.5 (Table 1).

Seaweed farms were mainly located in adjoining areas along the Mandapam and Rameswaram coasts of Tamil Nadu. They were operated primarily by women-centric Self-Help Groups (SHGs) or independent smallholder families. All farmers grew *K. alvarezii*, the red seaweed species in floating bamboo rafts of 3.6x3.6 dimension at a distance of 10-30 meters from the shore. Each operator owned 10-20 rafts and raised 5-6 cycles of the crop for 45 days a year. About 50-60 kg of planting material from previous crops was used to stock each raft. An average wet yield of 1177 kg/raft was obtained per raft per year from the sample units, which translates to 14.0 tonnes of wet yield per farm unit per year.

4.2. Determinants of adoption of cage farming and farm income

Cage farming is an emerging enterprise in the coastal regions. Multiple factors may influence cage farming adoption. Table 2 compares the key characteristics of adopters and non-adopters. The majority of respondents were male and fell within the age range of 30–60 years. Educational status differed significantly between adopters and non-adopters, with adopters demonstrating higher levels of education. Fishing was reported as the primary occupation by more than half of the respondents in both categories (54% adopters and 62% non-adopters). Non-adopters possessed significantly more experience in fishing and related activities than adopters. As anticipated, adopters of cage farming had greater exposure to technical training in the field and a larger proportion reported access to technical support from institutional sources. Additionally, adopters had greater access to institutional credit. Conversely, non-adopters owned larger land areas than adopters did.

Table 2. Descriptive statistics of the main outcome variable and covariates: Adopters *vis-à-vis* non-adopters of cage farming

Covariate	Mean (standard error)		t-statistic/z-statistic (p-value)
	Adopters (n = 129)	Non-adopters (n = 129)	
Outcome variables			
Total household income	1199400 (172544.6)	321645 (18151.2)	-5.0784*** (0.00)
Demographic variables			
Family size	4.42 (0.09)	4.52 (0.10)	0.73 (0.46)
Gender (male) #	0.75 (0.04)	0.89 (0.03)	2.95*** (0.00)
Age of the farmer#			
Below 30 years	0.16 (0.03)	0.22 (0.04)	1.08 (0.27)
Between 30 and 45 years	0.39 (0.04)	0.28 (0.04)	-1.75* (0.08)

Covariate	Mean (standard error)		t-statistic/z-statistic (p-value)
	Adopters (n = 129)	Non-adopters (n = 129)	
Between 45 and 60 years	0.35 (0.04)	0.41(0.04)	1.10 (0.27)
Above 60 years	0.10 (0.03)	0.08 (0.02)	-0.44 (0.65)
Education of the farmer#			
Illiterate	0.0 (0.0)	0.5 (0.0)	2.67*** (0.01)
Primary	0.05 (0.02)	0.04 (0.02)	-0.60 (0.54)
Secondary	0.57 (0.04)	0.68 (0.04)	1.84* (0.06)
Above secondary	0.37 (0.04)	0.22 (0.03)	-2.62*** (0.01)
Experience (fisheries/allied) (years)	6.80 (0.46)	11.76 (0.56)	6.78*** (0.00)
Number of earning family members	1.02 (0.11)	1.36 (0.12)	2.10** (0.04)
Economic/institutional variables			
Fishing as major occupation#	0.542 (0.04)	0.623 (0.04)	1.312 (0.18)
Number of relevant training attended	2.20 (0.21)	0.68 (0.11)	-6.39*** (0.00)
Access to technical support#	0.41 (0.04)	0.08 (0.02)	-6.12*** 0.00)
Land area owned (acres)	0.19 (0.04)	0.73 (0.17)	3.02*** (0.00)
Access to institutional credit#	0.58 (0.04)	0.16 (0.03)	-6.91*** (0.00)
Membership in societies#	0.46 (0.04)	0.37 (0.04)	-1.56 (0.11)

Note: # indicates the proportion of samples.

Table 3 presents the results of the Heckman model. The empirical strategy assumes that disparate sets of parameters determine a respondent's decision to adopt cage farming on the one hand, and the income obtained from the enterprise after taking it up on the other. Columns 3 and 4 present the results for the selection equation. Among the various demographic variables, factors like age and literacy of the respondents were found to determine the decision to adopt cage farming. Compared to respondents in the older age group, those below 30 years of age displayed a significantly greater inclination to take up cage farming. Similarly, the coefficients corresponding to the three educational attainment levels were significantly different. However, relatively greater educational attainment did not have any additional impact on the adoption of cage farming. Having fishing as a major occupation enhanced the odds of participating in cage farming. Nevertheless, a longer fishing experience had a negative impact on adoption. This suggests that older individuals who have been long engaged in fishing did not prefer cage farming, whereas younger individuals with some experience in fishing and allied activities were more inclined towards the activity compared to those with non-fishing backgrounds.

Table 3. Estimates of Heckman selection model for net income from cage farming

Covariate	Outcome equation		Selection equation	
	Coefficient	Std. Err.	Coefficient	Std. Err.
	(1)	(2)	(3)	(4)
Dependent variable: log (Net farm income from cage farming)				
Family size	0.175	0.105	0.022	0.143
Gender (male)	0.974***	0.347	0.897	0.510
Age (base = above 45 years)				
Below 30 years	1.174**	0.541	-1.957***	0.630
Between 30 and 45 years	0.292	0.273	0.082	0.386
Education (base = No formal education)				
Primary	2.163**	0.877	4.006***	1.511
Secondary	0.578**	0.285	4.407***	1.577
Above secondary	-	-	3.955***	0.908
Major occupation (fishing = 1)	-	-	0.878***	0.489
Experience (fisheries/allied) (years)	-0.051	0.105	-0.495**	0.125
Cage farming only (yes = 1)	0.065	0.251	-	-
Number of cages installed	0.136***	0.046	-	-
Number of earning family members	-	-	0.053	0.154
Relevant training attended (yes = 1)	-	-	-0.180	0.490
Number of relevant training attended	-0.035	0.102	0.300**	0.169
Access to technical support (yes = 1)	-0.790	0.513	1.994***	0.444
Land area owned (acres)	0.160	0.875	-2.627***	0.985
Area of farm unit (acres)	-0.054	0.947	-	-
Access to institutional credit (yes = 1)	0.392	0.301	0.694	0.514
Membership in societies	-0.542	0.532	-1.031*	0.513
Distance from the market (km)	0.051***	0.016	-	-
Distance from the nearest road (km)	0.082	0.088	-	-
Number of observations: 164; Wald chi2(17): 216.9***; Lambda: 0.599; Rho: 0.79; sigma: 0.757				

Training was found to significantly enhance the probability of cage farming adoption. Notably, a positive response to 'whether attended relevant training' alone was insufficient; rather, the greater the number of training sessions attended, the higher the likelihood of adoption. Access to technical support was another significant factor (at 1% level) that positively influenced adoption. The results also indicate that land ownership negatively influences the adoption of cage farming. This finding may be attributed to the availability of alternative income sources for those with larger land parcels. Access to institutional credit and membership in fishery/aquaculture societies has only a limited positive impact on facilitating adoption.

The results of the outcome equation presented in columns 1 and 2 of Table 3 provide notable insights into the factors that influence net income. Farms operated by male respondents and those below the age of 30 years were observed to generate significantly higher net incomes. The education level of the respondents was another positive factor that contributed to greater net farm income. As anticipated, farms with more cages earned higher net income. Other factors, such as exposure to relevant training, access to technical support, area of the farm unit, land area owned, access to institutional credit, membership of societies, and similar variables, did not demonstrate any significant relationship with farm income. Notably, farms that sold their harvested produce in distant markets realized better net income than those that found markets in closer proximity to their farms. This could be attributed to the better value realization in wholesale markets than in nearby primary markets.

4.3. Economic impact of cage farming: Evidence based on PSM analysis

The robustness of the impact of cage farming on income of adopters vis-à-vis non-adopters was checked by applying the PSM technique. The conditional probability of the households' adoption of cage farming was estimated using a probit regression framework, wherein the dependent variable assumed a value of '1' if the household is an adopter and '0' otherwise. The model included all observable covariates that affected cage farming adoption. The model was statistically significant at 1 % (Table 4).

Table 4. Estimated probit model for adoption of cage farming by sample households

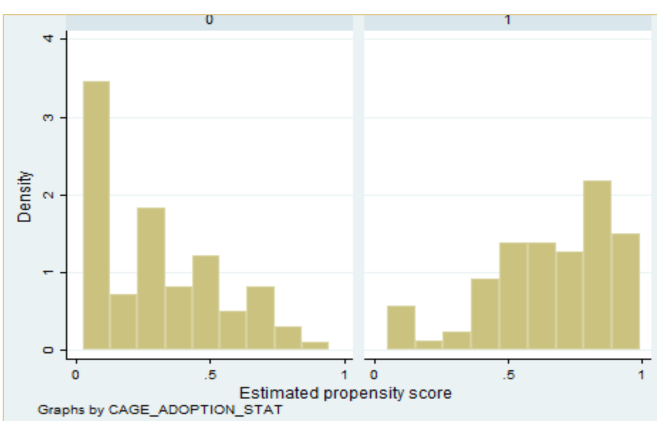
Covariate	Coefficient	Std. Err.
Dependent variable: Adoption status of cage farming (adopter = 1)		
Family size	-0.160	0.096
Gender (male)	0.736**	0.326
Age (base = above 45 years)		
Below 30 years	-0.974***	0.380
Between 30 and 45 years	-0.074	0.272
Education (base = No formal education)		
Primary	5.601***	1.008
Secondary	5.362***	0.819
Above secondary	5.261***	0.841
Major occupation (fishing = 1)	0.628**	0.262
Experience (fisheries/allied) (years)	-0.142***	0.025
Number of earning family members	-0.104	0.079
Relevant training attended (yes = 1)	0.117	0.322
Number of relevant training attended	0.203**	0.083
Access to technical support (yes = 1)	1.141***	0.294
Access to institutional credit (yes = 1)	1.544***	0.336
Membership in societies	0.298	0.464

Covariate	Coefficient	Std. Err.
Dummy for coastal water cage (yes = 1)	-0.416	0.484
Dummy for Kerala (yes = 1)	0.586	0.684
Dummy for Tamil Nadu (yes = 1)	0.525	0.511
Constant	-5.230	
Number of observations: 254; LR chi^2 (17): 162.2***; Pseudo R^2: 0.46		

The results indicated a statistically significant difference between the treated and control groups with respect to age, gender, education, experience in fishing and allied activities, training, access to technical support, and availability of institutional credit. These findings are consistent with the results of the Heckman analysis.

Propensity scores were calculated for each observation in the treatment and control groups, and the region of common support was determined (0.045, 0.999) to facilitate an unbiased comparison. Of the 254 observations utilized in the estimation, 222 fell within the region of common support. Within this region, the mean estimated propensity score was 0.575, with a standard deviation of 0.33. The distributions of propensity scores for adopters and non-adopters after matching are shown in Fig. 2. The estimates were categorized into five optimal blocks, such that the mean propensity score in each block for the treatment and control blocks did not differ significantly. The balancing property was satisfied, indicating that after controlling for the observed covariates, the treatment was independent of the unit characteristics.

Fig. 2. Histogram of propensity scores of adopters and non-adopters of cage farming after matching



After achieving a balance of the covariates across the treatment and comparison groups, nearest-neighbor matching and kernel matching were applied. The estimated ATT of the impact of cage farming on the household income of treated households is presented in Table 5.

Table 5. ATT estimates (₹ Million) corresponding to the household income of the sample households

Matching method	Number of matched observations		ATT	Std. Err.	t-value
	Adopter	Non-adopter			
Nearest neighbour method	128	36	0.663***	1.93	3.439
Kernel matching method	128	94	0.707***	1.77	3.989

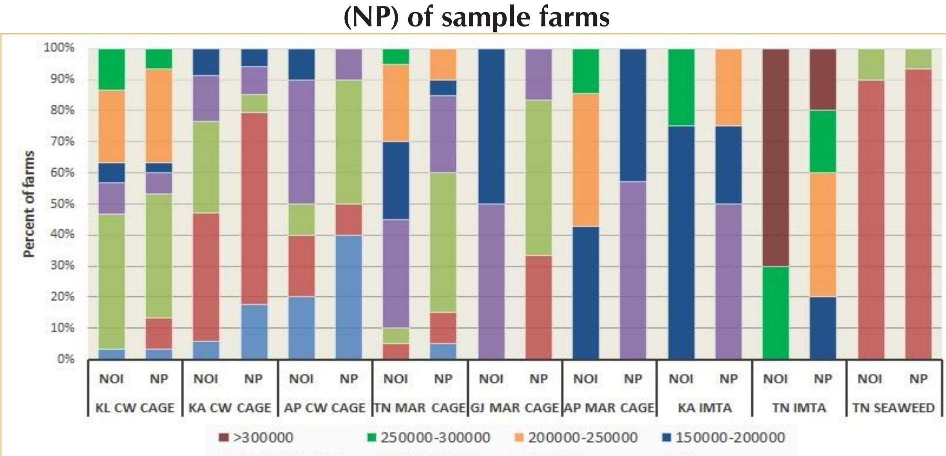
Note: The unit for the outcome variable is 000 rupees.

The ATT estimates were highly significant. The gains in household income attributable to cage farming were estimated to be ₹0.663 -0.707 million. The results indicate the notable economic impact of cage farming, pointing towards its future potential as a promising livelihood avenue for coastal fishermen.

4.4. Sustainability status of mariculture

The estimated techno-economic parameters for the selected mariculture enterprises are listed in Table 6. Significant variations exist in these parameters across enterprises and regions. Access to institutional credit and markets, as well as orientation towards value addition, is inadequate for enterprises. The open-sea cage culture units in Andhra Pradesh demonstrated higher profitability compared to other locations. Similarly, coastal water cage units in Kerala exhibited greater profitability (Fig. 3). Although marine cage farmers generally performed better in terms of absolute indicators of profitability due to the larger size of culture units, they underperformed in terms of relative profitability indicators, such as ROI, BCR, and OR (Fig. 4). Several open sea cage culture units in Tamil Nadu, and coastal water cage culture and IMTA in Karnataka and Andhra Pradesh incurred financial losses.

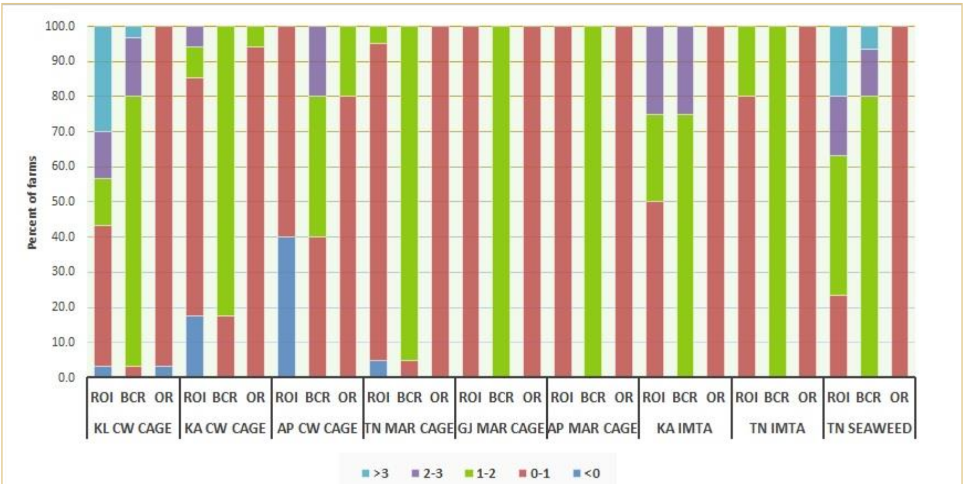
Fig. 3. Distribution of Net Operating Income (NOI) and Net Profit (NP) of sample farms



Notes: For seaweeds, income estimates are reported for a batch of 10 rafts each for the sample farmers; Profitability is expressed in Indian rupees (1 Indian Rupee (INR) = 0.012 US Dollars)

KL CW CAGE: Coastal water cage, Kerala; KA CW CAGE: Coastal water cage, Karnataka; AP CW CAGE: Coastal water cage, Andhra Pradesh; TN MAR CAGE: Marine cage, Tamil Nadu; GJ MAR CAGE: Marine cage, Gujarat; AP MAR CAGE: Marine cage, Andhra Pradesh; KA IMTA: IMTA, Karnataka; TN IMTA: IMTA, Tamil Nadu; TN SEAWEED: Seaweed, Tamil Nadu

Fig. 4. Distribution of economic viability indicators of sample farms



Notes: same as Fig. 2

Table 6. Estimated sustainability indicators associated with selected mariculture enterprises in sample locations in India, 2022

Key Indicators / metrics	Open sea cage farming			Coastal water cage farming			IMTA		Seaweed farming
	Tamil Nadu	Andhra Pradesh	Gujarat	Karnataka	Kerala	Andhra Pradesh	Tamil Nadu	Karnataka	Tamil Nadu
A. Techno-economic indicators									
Permanence in activity (PA)	1.7 (0.9)	11.4 (5.5)	7.3 (2.5)	4.9 (2.7)	5.1 (3.2)	2.8 (1.56)	4.9 (3.0)	8.8 (4.8)	7.8 (3.9)
Capital self-sufficiency (CS) (%)	20.0	28.6	100.0	29.4	80.0	10.0	0.0	NA	100
Family labour share (FL) (%)	36.6	0.0	14.4	84.3	58.8	81.3	47.8	87.2	54.5
The legitimacy of access (LA) (%)	0.0	0.0	0.0	100.0	16.7	0.0	0.0	100.0	0.0
Formal training (FT) (%)	100.0	85.7	100.0	79.4	100.0	100.0	100.0	100.0	100.0
Access to technology (AT) (%)	100.0	85.7	100.0	97.1	100.0	100.0	100.0	100.0	100.0
Quality seed (QS) (%)	100.0	100.0	25.0	47.1	100.0	100.0	100.0	100.0	-
Formulated feed (FF) (%)	0.0	100.0	0.0	23.5	83.3	70.0	0.0	0.0	-

Key Indicators / metrics	Open sea cage farming			Coastal water cage farming			IMTA		Seaweed farming
	Tamil Nadu	Andhra Pradesh	Gujarat	Karnataka	Kerala	Andhra Pradesh	Tamil Nadu	Karnataka	Tamil Nadu
Institutional credit access (IC) (%)	0.0	0.0	0.0	64.7	27.0	0.0	0.0	25.0	0.0
Institutional credit availed (ICA) (INR)	0.0	0.0	0.0	NA	1,10,570	0.0	0.0	NA	0.0
Diversity of markets (DIV)	1	1	3	4	3	1	2	5	1
Marketing agreement (MA) (%)	0.0	0.0	0.0	0.0	0.0	0.0	20.0	0.0	0.0
Unfair market practices (UMP) (%)	0.0	0.0	0.0	100.0	13.0	70.0	70.0	100.0	100.0
Market commission rate (CR) (%)	Nil	5.0	Nil	7.0	Nil	3.5	Nil	Nil	Nil
Value addition orientation (VAO) (%)	0.0	0.0	0.0	0.0	47.0	0.0	0.0	0.0	0.0
Net operating Income (NOI) (INR)	Results depicted in Fig. 2 below								
Net profit (NP) (INR)									
Returns on Investment (ROI)	Results depicted in Fig. 3 below								
Benefit-Cost Ratio (BCR)									
Operating Ratio (OR)									
B. Techno-environmental indicators									
Species diversity (SD)	1	2	3	3	4	3	2	6	1
Mechanization (MCH) (%)	0.0	71.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Renewable energy access (RE) (%)	0.0	100.0	37.5	5.9	30.0	40.0	0.0	0.0	0.0
Management adequacy (MA) (%)	10.0	57.1	0.0	5.9	56.7	20.0	0.0	0.0	0.0
Farm surveillance (FS) (%)	0.0	85.7	0.0	100.0	93.3	90.0	0.0	0.0	0.0
Antifouling management (AFM) (%)	0.0	100.0	0.0	100.0	56.7	100.0	0.0	100.0	0.0
Water quality monitoring (WQM) (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Key Indicators / metrics	Open sea cage farming			Coastal water cage farming			IMTA		Seaweed farming
	Tamil Nadu	Andhra Pradesh	Gujarat	Karnataka	Kerala	Andhra Pradesh	Tamil Nadu	Karnataka	Tamil Nadu
Crop holiday management (CHM) (%)	100.0	100.0	100.0	47.1	63.3	100.0	100.0	50.0	100.0
C. Social indicators									
Institutional linkage (IL) (%)	100.0	85.7	100.0	100.0	100.0	100.0	100.0	100.0	100
Social engagement (SE) (%)	100.0	71.4	37.5	85.3	23.0	50.0	80.0	100.0	100
Employment generation (EG) (man-days/unit)	321.4 (56.6)	195.3 (23.8)	175 (54.2)	94.3 (41.9)	145 (45.4)	196 (70.3)	395.7 (111.0)	90.2 (4.2)	98.7 (36.0)
Gender inclusion (GI) (%)	33.3	24.8	8.3	20.6	13.3	34.5	51.8	19.6	57.9
Crew insurance (CI) (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Crew safety (CS) (%)	0.0	85.7	37.5	94.1	10.0	100.0	0.0	100.0	0.0
Social protection (SP) (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Number of observations	20	7	14	34	30	10	10	4	30

Note: Figures in parentheses indicate estimates of standard deviation; 1 Indian Rupee (INR) = 0.012 US Dollars

The majority of farms were observed to understock their culture units primarily due to a shortage of quality seeds and their relatively high cost. Only the lobster cage farms in Gujarat exhibited a stocking density greater than that recommended, as they were Capture-Based Aquaculture (CBA) units. Numerous farmers practicing coastal water cage farming in Kerala have also reported overstocking their cages. Except those in Visakhapatnam (71.4%), none of the farm units reported any mechanization or automation of their operations. In the latter case, farmers reported attempting automated feeding in their cages on a trial basis with technical support from the Visakhapatnam Center of ICAR-CMFRI. The utilization of solar energy in farms for lighting, surveillance, and powering other minor farm operations is gradually becoming more prevalent in cage farms. Management Adequacy (MA), a measure to determine the level of adoption of disease control, hygiene management, and general health management of farm stock, was observed to be relatively higher among marine cages in Andhra Pradesh (57.1%) and coastal water cage farms in Kerala (81.8%). Almost all coastal water cage farms adopted farm surveillance measures, such as closed-circuit cameras or watch-and-ward mechanisms; however, their adoption in marine-based enterprises (except in Visakhapatnam) was low.

Among the indicators of social sustainability, farms demonstrated high scores in Institutional Linkage (IL) and Social Engagement (SE), as they maintained strong connections with various research and extension agencies. These linkages were primarily utilized to acquire technological updates on farming; gain access to financial, technical, and extension assistance; develop skills through training programs; and enhance farm management capabilities. The indicators also suggest that mariculture enhanced employment opportunities and gender inclusion. Employment estimates varied across enterprises and locations, ranging from 94 to 396 person-days per unit per crop. The highest average person-day requirement was observed for IMTA (395.7 person-days/unit) and marine cage farms (321.4 person-days/unit) in Tamil Nadu, whereas coastal water IMTA in Karnataka (90.2 person-days/crop) and seaweed farming (98.7 person-days/crop) in Tamil Nadu exhibited lower employment figures. The results pertaining to crew insurance (CI) and social protection (SP) were absent at all locations, indicating significant gaps in the social dimensions of sustainability. However, the farm units in Andhra Pradesh and Karnataka maintained effective measures to ensure crew safety at work (floaters, life jackets, hand gloves, rubber shoes, etc.).

Farms generally exhibit poor performance in terms of technical and environmental indicators. Significant deficiencies were observed in mechanization, utilization of renewable energy, disease and hygiene management, farm surveillance, antifouling, and water quality. Notably, most farms, with the exception of cage farms engaged in lobster fattening in Veraval (Gujarat) and coastal water cage farms in Kerala, were predominantly observed to under-stock fish seeds, resulting in suboptimal crop yields. Addressing this deficiency through enhanced seed availability and extension interventions could substantially improve the economic viability of these units. The profitability of farms at numerous locations was also affected by several input-side constraints and other extraneous factors. For instance, coastal water cage farmers in Andhra Pradesh reported that delays in obtaining fish seeds resulted in the late commencement of culture, thereby curtailing the culture period. Some farmers also reported mortality due to wastewater infusions from neighboring industrial units.

Yield enhancement, a primary pillar of SI, requires attention, which can be achieved through optimal seed stocking, increased culture intensity via polyculture of suitable species, and scientific management of various biotic and abiotic constraints. Prospective interventions include regular carrying capacity and water quality assessments, utilization of disease-free SPF seeds, disease surveillance, implementation of aquatic animal health codes applicable to open water bodies, measures to prevent siltation and biofouling, monitoring of invasive species incidence, and realignment of crop schedules to accommodate salinity and temperature fluctuations in water bodies through regular monitoring (OIE 2019; Fox et al. 2020; Wanja et al. 2020). The adoption of IMTA is limited. However, the enhanced growth and higher yields of extractive species, as well as the potential for biofouling mitigation around cages, present considerable future opportunities in India. Similarly, the seaweed farming sector requires an increased supply of planting material, either through genetic improvement, mass multiplication, or the introduction of suitable exotic species, following appropriate screening for potential negative ecological consequences (Johnson et al., 2021).

5. Conclusions

Although predominantly smallholder-oriented, mariculture is a potential source of marine fish. Over the past 15 years, significant advancements have been made in the breeding, seed production, and growth of marine finfish and shellfish species in artificial enclosures and structures, facilitating their economically viable cultivation in open, coastal, and estuarine waters. The results of this study indicate that cage farming can substantially increase farm incomes.

Given the early stages of development, the technical and human resource prerequisites for enabling resource-poor coastal inhabitants to engage in capital-intensive mariculture activities are substantial. There are significant deficiencies in the key indicators of sustainability, including the legitimacy of access to water bodies, quality seed and feed, institutional credit and market, automation of farms and renewable energy, farm surveillance, crew safety, and social protection.

Specific recommendations in regard to the aforementioned include: (i) development of marine spatial plans (MSP) for optimal allocation of available ocean space; (ii) introduction of legislation at appropriate levels to support leasing and licensing arrangements, with particular consideration for marginalized coastal communities; (iii) implementation of measures to ensure adequate supply of quality seed and feed through channelling public funding and incentivizing the private sector; (iv) strengthening of food safety and health management protocols in mariculture farms; (v) development of mandatory guidelines on good farming practices (e.g., measures for anti-fouling, water quality monitoring, crop holiday management, safety and security measures) to obtain farm registration; (vi) enhancement of multi-disciplinary research on mariculture systems; (vii) implementation of market reforms for the development of competitive value chains; (viii) introduction of specialized schemes to support auxiliary prerequisites such as credit, insurance, and other support services; and (ix) promotion of group farming, cooperative farming, and FFPOs among mariculture farmers (FAO, 2016). The mariculture farmers can be brought under the ambit of collective farming groups such as FFPOs through initial government patronage and facilitation for group mobilization, technical backstopping, skill upgradation, provision of credit and insurance support, and awareness generation hinging on successful examples. Attracting entrepreneurs to mariculture requires attention by showcasing its profitability, growth potential, and sustainability while reducing barriers to entry. This involves streamlining regulations, improving access to resources and technical support, and fostering a supportive ecosystem. Addressing concerns about risk, environmental impact, and social responsibility is also crucial. A multi-pronged approach focusing on economic viability, environmental consciousness, and social responsibility will attract innovative entrepreneurs to this promising sector.

The governance of mariculture presents significant complexities due to the presence of diverse stakeholders with conflicting interests as well as concerns regarding equity and enforcement challenges. Numerous contentious issues require prompt resolution, including ownership and operational structures (cooperative/corporate/private/other), engagement within various social and political domains, and alignment with intersecting sectors (Percy et al. 2013; Davies et al. 2019). Of paramount importance is the establishment of appropriate institutions and governance mechanisms to ensure that the future expansion of mariculture development adheres to a precautionary approach to environmental sustainability and is guided by the Ecosystem Approach to Aquaculture (EAA) to maintain the resilience of interconnected social-ecological systems.

References

Alagarswami, K. 1974. Development of pearl culture in India and scope for a pearl culture industry. In: R. V. Nair (Ed.), *Proceedings of the Group discussion on pearl culture* (pp. 4-19). CMFRI, Cochin.

Anuraj A., Suresh, B. P. P., Raghu, R. K., Vaidya, N. G., Dube, P. Pal, M., Rathod, H., and Anjulekshmi, P. 2022. IMTA cages yield a bountiful harvest. *Cadalmin* (173), Newsletter, April-June 2022, ICAR-CMFRI. Available at CMFRI Newsletter No.173 April - June 2022 - CMFRI Repository.

Appukuttan K. K., and Alagarswami, K., 1980. Culture of brown mussel *Perna indica* at Vizhinjam. *Marine Fisheries Information Service, Technical and Extension Series* 16: 11-13, Central Marine Fisheries Research Institute, Kochi.

Anonymous. 2022. ICAR-CMFRI extends technical guidance to launch India's first open sea cage farm under mariculture policy. *Aquaculture Spectrum* 5(10): 70.

Arasu A. R. T., Kailasam, M., and Sundaray J. K. 2009. *Asian seabass, fish seed production and culture*. CIBA Special Publication 42, Central Institute of Brackishwater Aquaculture, Chennai, India, 158.

Aswathy, N., Joseph, I., Ignatius, B., and Joseph, S. 2020. *Economic viability of cage fish farming in India*. CMFRI Special Publication 134. Central Marine Fisheries Research Institute, Kochi.

Ayyappan, S., Jena, J. K., Lakra, W. S., Gopal, T. K. S., Gopalakrishnan, A., Vass, K. K., Sahoo, P. K. and Chakrabarti, R. 2015. Fisheries Sciences. In: R. B. Singh (Ed.), *100 Years of Agricultural Sciences in India*. National Academy of Agricultural Sciences, New Delhi.

Balasubramanian, C. P., Mhaskar, S. S., Sukumaran, K., Panigrahi, A., Vasagam, K., Kumararaja, P., et al. 2018. Development of integrated multi-trophic aquaculture (IMTA) for tropical brackishwater species in Sindhudurg district, Maharashtra, west coast of India, *Indian Journal of Fisheries* 65(1): 59-64.

Becker, S. O., and Ichino, A. 2002. Estimation of average treatment effects based on propensity scores. *The Stata Journal* 2(4): 358-377.

Bostock, J., McAndrew, B., Richards, R., Jauncy, K., Telfer, T., Lorenzen, K. et al. 2010. Aquaculture: Global status and trends. *Philosophical Transactions of the Royal Society B: Biological Sciences* 365: 2897–2912.

Chakraborty, K., Vijayagopal, P. and Gopalakrishnan, A. 2018. Nutraceutical products from seaweeds- wonder herbs of the oceans. *Marine Fisheries Information Service; Technical and Extension Series* 237: 7-12.

Chopin, T., Robinson, S. M. C., Troell, M., Neori, A., Buschmann, A. H. and Fang, J. 2008. Multitrophic integration for sustainable marine aquaculture. In: S. E. Jørgensen and B. D. Fath (Eds.), *The Encyclopedia of Ecology, Ecological Engineering* (pp. 2463-2475) Vol 3. Elsevier, Oxford.

Costello, C., Cao, L., Gelcich, S., Cisneros-Mata, M. A., Free, C. M., Froehlich, H. E. et al. 2020. The future of food from the sea. *Nature* 588: 95–100.

Davies, I. P., Carranza, V., Froehlich, H. E., Gentry, R. R., Kareiva, P., and Halpern, B. S. 2019. Governance of marine aquaculture: Pitfalls, potential, and pathways forward. *Marine Policy* 104: 29-36.

Divu, D. N., Mojjada, S. K., Pokkathappada, A. A., et al. 2020. Decision-making framework for identifying best suitable mariculture sites along north-east coast of Arabian Sea, India: A preliminary GIS-MCE based modelling approach. *Journal of Cleaner Production* 284 (15): 124760.

Edwards, P., Zhang, W., Belton, B., and Little, D. C. 2019. Misunderstandings, myths, and mantras in aquaculture: Its contribution to world food supplies has been systematically over-reported. *Marine Policy* 106: 103547.

FAO. 2016. *Sustainable intensification of aquaculture in the Asia-Pacific region: Documentation of successful practices*. Miao, W. and Lal, K.K. (Eds.), Food and Agricultural Organization of the United Nations, Bangkok, Thailand.

Fox, M., Christley, R., Lupo, C., Morre H., Service, S., and Campbell, K. 2020. Preventing and mitigating farmed bivalve disease: a Northern Ireland case study. *Aquaculture International* 28: 2397–2417.

GoI. 2017. *National policy on marine fisheries*. Ministry of Agriculture and Farmers Welfare, Government of India.

Gopakumar, G., Nair, K. R. M., and Kripa, V. 2007. Mariculture research in India - Status, constraints and prospects. In: M. J. Modayil and N. G. K. Pillai (Eds.), *Status and Perspectives in Marine Fisheries Research in India* (pp. 316–361). CMFRI Diamond Jubilee Publication, Central Marine Fisheries Research Institute, Kochi, India.

Gopalakrishnan, A., Ignatius, B., and George, G. 2017. India's largest fisheries research body turns 70- CMFRI's legacy and a few recent achievements. *Fishing Chimes* 37(1): 38-44.

Gopalakrishnan, A., Kirubagaran, R., John, G., Ponniah, A. G., Gopakumar, G., Mohamed, K. S. et al. 2019. *Draft National Mariculture Policy 2019*. Report of the committee constituted by the National Fisheries Development Board, Ministry of Fisheries, Animal Husbandry and Dairying, Government of India, CMFRI Marine Fisheries Policy Series No. 17/2020, 22p.

Heckman, J. 1979. Sample selection bias as specification error. *Econometrica* 47(1): 153-161.

Jena, J. K., Gopalakrishnan, A., Ravisankar, C. N., Lal, K. K., Das, B. K., Das, P. C., Panigrahi, A. K., Shinoj, P. and Madhu, V. R. 2022. Achievements in fisheries and aquaculture in independent India. In: H. Pathak, J. P. Mishra and T. Mohapatra (Eds.), *Indian Agriculture after Independence*. Indian Council of Agricultural Research, New Delhi.

Johnson, B., Divu, D., Jayasankar, R., Ranjith, L., Dash, G., Megarajan, S. et al. 2020. Preliminary estimates of potential areas for seaweed farming along the Indian coast. *Marine Fisheries Information Service; Technical and Extension Series* 246: 14-28.

Johnson, B., Jayakumar, A., Abdul Nazar, A. K., Tamilmani, G., Sakthivel, M., Rameshkumar, P., Anikkuttan, K. K., and Sankar, M. 2021. Climate resilient mariculture technologies for food and nutritional security, In: V. Venkatramanan et al. (Eds.), *Exploring Synergies and Trade-offs Between Climate Change and the Sustainable Development Goals*, Springer Nature.

Johnson, B., Narayanakumar, R., Abdul Nazar, A. K., Kaladharan, P., and Gopakumar, G. 2017. Economic analysis of farming and wild collection of seaweeds in Ramanathapuram District, Tamil Nadu. *Indian Journal of Fisheries* 64(4): 94-99.

Kaliaperumal, N., and Kalimuthu, S. 1997. Seaweed potential and its exploitation in India. *Seaweed Research and Utilization* 19(1-2): 33-40.

Krishnan, M., and Narayanakumar, R. 2013. *Social and economic dimensions of carrageenan seaweed farming*. FAO Fisheries and Aquaculture Technical Paper 580: 163-184.

Kuriakose, P. S. 1980. Opensea raft culture of green mussel at Calicut. In: K. N. Nayar, S. Mahadevan, K. Alagarswami and P.T. Meenakshisundaram (Eds.), *Coastal Aquaculture: Mussel Farming-Progress and Prospects* (pp. 33–38). CMFRI Bulletin 29, India.

Little, D. C., Murray, F. J., Leschen, W., and Waley, D. 2013. Socio-economic factors affecting aquaculture site selection and carrying capacity. In: L.G. Ross, T.C. Telfer, L. Falconer, D. Soto & J. Aguilar-Manjarrez (Eds.) *Site selection and carrying capacities for inland and coastal aquaculture* (pp. 103–115). FAO/Institute of Aquaculture, University of Stirling.

Little, D. C., Young, J. A., Zhang, W., Newton, R. W., Mamun, A. A., and Murray, F. J. 2018. Sustainable intensification of aquaculture value chains between Asia and Europe: A framework for understanding impacts and challenges, *Aquaculture* 493: 338-354.

Mantri, V. A., Dineshkumar, R., Yadav, A. et al. 2022. How profitability assessment parameters score under large-scale commercial cultivation of different agarophyte seaweeds along the south-eastern coast of India. *Aquaculture International* DOI:10.1007/s10499-022-00866-y.

NFDB. 2018. *Guidelines for sea cage farming in India: Towards blue revolution*, National Fisheries Development Board, Ministry of Agriculture and Farmers Welfare, Government of India.

OIE. 2019. *The aquatic animal health code* (22nd Ed.). World Organization for Animal Health. Available at: http://www.oie.int/standardsetting/aquatic-code/acces-online/ [Accessed 20March, 2021]

Parappurathu, S., Menon, M., Jeeva, C., et al. 2023. Sustainable intensification of small-scale mariculture systems: Farm-level insights from the coastal regions of India. *Frontiers in Sustainable Food Systems* 7.

Percy, D. R., Hishamunda, N., and Kuemlangan, B. 2013. Governance in marine aquaculture: the legal dimension. In: A. Lovatelli, J. Aguilar-Manjarrez & D. Soto. (Eds)., *Proceedings of the FAO technical workshop on expanding mariculture farther offshore: Technical, environmental, spatial and governance challenges, FAO Fisheries and aquaculture* 24: 245–262.

Pretty, J. 1997. The sustainable intensification of agriculture. *Natural Resources Forum* 21: 247–256.

Ranjan, R., Muktha, M. Ghosh, S., Gopalakrishnan, A., Gopakumar, G., and Joseph, I. 2017. *Prioritized species for mariculture in India*, ICAR-Central Marine Fisheries Research Institute, Kochi.

Rao, G. S., Joseph, I., Philipose, K. K., and Mojjada, S. K. 2013. *Cage Aquaculture in India*. Central Marine Fisheries Research Institute, Kochi.

Rao, P. V. S., and Mantri, V. A. 2006. Indian seaweed resources and sustainable utilization: Scenario at the dawn of a new century. *Current Science* 91: 164–174.

Rey-Valette, H., Clement, O., Aubin, J., Mathe, S., Chia, E., Legendre, M., et al. 2008. *Guide to the co-construction of sustainable development indicators in aquaculture*. Montpellier, France.

Rey-Valette, H., Clement, O., Aubin, J., Mathe, S., Chia, E., Legendre, M., et al. 2010. An approach to co-construct sustainable development indicators in aquaculture. In: *IIFET 2010 Montpellier Proceedings*, Montpellier, France.

Rosenbaum, P.R. and Rubin, D. B. 1983. The central role of propensity score in observational studies for casual effects. *Biometrika* 70(1): 41-55.

Silas, E. G., and Kalimuthu, S. 1987. *Commercial exploitation of seaweeds in India*. CMFRI Bulletin 41: 55-59.

Smith, J., and Todd, P. 2005. Does matching over Lalonde's critique of nonexperimental estimators? *Journal of Econometrics* 125(1-2): 305-353.

Thivy, F. 1964. Marine algal cultivation. *Salt Research and Industry* 1(1): 23–28.

Wanja, D. W., Mbuthia, P. G., Waruiru, R. M., Mwadime, J. M., Bebora, L. C., Nyaga, P. N., and Ngowi, H. A. 2020. Fish husbandry practices and water quality in central Kenya: Potential risk factors for fish mortality and infectious diseases. *Veterinary Medicine International* 6839354 DOI:10.1155/2020/6839354.

Annexure A1. Sampling framework for primary data collection in selected coastal states of India, 2022

State	District	Location	Number sample respondents under			
			Marine cage farming	Coastal water cage farming	IMTA	Seaweed farming
Andhra Pradesh	Visakhapatnam	Visakhapatnam	07			
	Krishna	Lakshmipuram		03		
		Pedapalem		07		
Tamil Nadu	Ramanathapuram	Kalaimangundu	07			
		Chinnapalam	04			
		Thankachimadam	03			
		Kundhukal	06			
		Mandapam			10	25
		Rameswaram				05
Kerala	Ernakulam	Gothuruthu		05		
	Alappuzha	Thrikkunnapuzha		08		
		Arattupuzha		07		
	Kollam	Kollam		10		
Karnataka	Uttara Kannada	Karwar		08		
		Kumta		07		
		Bhatkal		05		
	Udupi	Uppunda		04		
		Byndoor		04	04	
		Kundapura		06		
Gujarat	Gir Somnath	Veraval	4			
	Porbandar	Porbandar	2			
	Kutch	Kutch	4			
Diu	Diu	Diu	4			
All			**41**	**74**	**14**	**30**

Annexure A2. Sampling framework for data collected covering adopters and non-adopters of cage farming, 2023.

State	District	Sample size		Total
		Adopters	Non-adopters	
Kerala	Ernakulam	40	40	80
	Alappuzha	39	40	79
Tamil Nadu	Ramanathapuram	30	30	60
Karnataka	Udupi	20	20	40
Total		**129**	**130**	**259**

Annexure A3. Summary of key dimensions, criteria, and indicators as per PCI approach to assess the level of sustainability associated with selected mariculture enterprises in sample locations in India, 2022

Dimension (Principle)	Broad Criteria	Key Indicators /metrics
A. Techno-Economic dimensions		
I. Entrepreneurial readiness of farmers/ entrepreneurs	Farming experience; Access to capital; General education / Technical skills; Access to technology and outside technical expertise; Availability of family/hired labour; Owned land/leased land/ water body; Technical training	Permanence in activity (PA) = Average farming experience of the farmer in years
		Capital self-sufficiency (CS) = Percent of farm operators in the sample having met more than half of capital expenditure from own funds
		Family labour share (FL) = Average share of family labour in total labour across sample farms
		The legitimacy of access (LA) = Percent of the sample farm units that reported ownership rights or existence of legal contract over the water body used for culture
		Formal training (FT) = Percent of sample farms that reported having acquired formal training by the proprietor in mariculture
		Access to technology and institutions (AT) = Percent of sample farms reported accessing technological support from a formally recognized source (Research institute/KVK, etc.)
II. Backward linkages with input markets and support services	Level of access to quality fish seeds/ fingerlings, quality feeds, and other inputs; Access to institutional credit	Quality seed use (QS) = Percent of sample farms that reported sourcing quality seeds from credible sources (%)
		Formulated feed use (FF) = Percent of sample farms that reported using formulated feeds
		Institutional credit access (IC) = Percent of sample farms that have reported an outstanding credit from institutional sources
		Institutional credit availed (ICA) = Average value (Indian Rupees, INR) of the institutional loan across sample farms

Dimension (Principle)	Broad Criteria	Key Indicators /metrics
III. Market access and value chain integration	Access to markets for the sale of fish harvested; Fair choice of markets (diversity of markets) to sell harvested fish; Assured price at farm gate; Absence of unfair trade practices; Linkage with value addition /processing facilities	Diversity of markets (DIV) = Number of marketing options (first sale) exercised by sample units
		Marketing agreement (MA) = Percent of sample farms that reported entering into a prior formal contract for marketing their produce
		Unfair market practices (UMP) = Percent of sample farms that reported one or more unfair market practices encountered while selling their produce
		Market commission rate (CR) = Prevailing commission rate (%) at the point of the first sale
		Value addition orientation (VAO) = Percent of sample farms having direct linkages with value addition centers
IV. Profitability and viability of the enterprise	Level of existing production and yield; Economic returns over the cost incurred; Scope for scale-up	Net operating Income (NOI) = (Gross returns) – (Operating costs) (INR)
		Net profit (NP) = (Gross returns) – (Total cost) (INR)
		Returns on Investment (ROI) = (Net profit)/(Initial investment costs)
		Benefit-Cost Ratio (BCR) = Present value of benefits/Present value of costs
		Operating Ratio (OR) = Operating cost/Gross revenue
B. Techno-environmental dimensions		
I. Technical measures for crop sustenance	Adoption of recommended stocking density; Diversity of products; degree of mechanization; Use of renewable sources of energy; Measures adopted for disease control; Standard management practices for hygiene and healthy fish stock; farm surveillance mechanisms	Stocking density deviation (SDD) = Percent deviation w.r.t recommended stocking density* for each species cultured
		Species diversity (SD) = Number of all farmed species (fish/shellfish/seaweed) across sample farms over the last three crop seasons
		Mechanization (MCH) = Percent of sample farms having reported using any major means of farm mechanization (automation of farm operations/ climate control, etc.)
		Renewable energy access (RE) = Percent of sample farms that depend mainly on renewable sources (solar, wind, etc.) for energy
		Management adequacy (MA) = Percent of sample farms with at least one scientific measure adopted for disease control, hygiene management, and maintenance of healthy fish stock
		Farm surveillance (FS) = Percent of sample farms with measures in place for surveillance of the farm against poaching risk

Dimension (Principle)	Broad Criteria	Key Indicators /metrics
II. Measures in place to ensure environmental sustainability	Measures for antifouling; Measures to check water body pollution; Crop calendar and crop holidays practiced	Water quality monitoring (WQM) = Percent of sample farms with at least one measure in place for water quality monitoring
		Crop holiday management (CHM) = Percent of sample farms observing crop holidays for at least 3 months in a year
C. Social dimensions		
I. Social capital/ community capital for sustainable intensification	Access to scientific /technical institutions for technical/ extension support; Co-operatives/ FPOs/NGOs; Government policies/ legislations.	Institutional linkage (IL) = Percent of sample farms having reported working linkage with scientific and technical institutions for technical and extension support
		Social engagement (SE) = Percent of the sample respondents having reported membership in Co-operatives/FPOs/other similar organizations
II. Potential for enhancing social welfare	Measures in place for crew safety; Potential for employment generation; Potential for gender inclusivity and women empowerment; Measures adopted for social protection; Contribution to the local economy through the local sale of produce	Employment generation (EG) = Average employment generated per crop (man-days)
		Gender inclusion (GI) = Average women-labour days generated as a share of the total labour generated per crop
		Crew insurance (CI) = Percent of sample farms reported having farm crew insurance
		Crew safety (CS) = Percent of sample farms reported having to have safety gears for the farm crew
		Social protection (SP) = Percent of sample farms reported having enrolled in government social protection programs

*Notes: *The recommended stocking density estimates were mainly obtained from NFDB (2018). Standard stocking density recommendation from ICAR-CMFRI was used for species that are not included in NFDB (2018). Mid-point is taken in cases where recommended stocking density is expressed as a rang*