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Mapping of potential sea-cage farming sites through spatial modelling: Preliminary operative suggestions to aid sustainable mariculture expansion in India

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Abstract

Sea cage farming in marine open waters is considered as the most viable technique in Indian mariculture to enhance production. Owing to the support of the government in research and development, and policy initiatives, marine cage farming is progressing steadily in the country. Technological guidance from research institutions and financing under the ambitious *"Pradhan Mantri Matsya Sampada Yojana (PMMSY)"* and blue growth mission objectives have inspired stakeholders and fisheries administrators in maritime states to explore open sea cage culture. Site selection is a key parameter affecting the success of cage culture systems and, technically analysed geo-referenced demarcation of spatial information is necessary for minimising the risks. Thus, in the light of rising demand for spatial allocation of coastal areas, the present study identifies and aggregates locations within 3 km of the coastline, that have the potential for sea cage farming operations in the country. The site suitability was examined based on optimal standards required for the prospective candidate species selected for mariculture in India. The locations were vectorised in a GIS platform, and the potential areas available for sea cage installations were demarcated. An optimised site suitability schema was developed for the spatial demarcation of potential site selection. The preliminary results identified 134 sites covering a total area of 46,958.2 ha suitable for marine cage culture along Indian territorial waters. Among the coastal states, the top three states holding the maximum area suitable for sea cage farming are Andhra Pradesh (11,792 ha), Gujarat (11,572.2 ha) and Tamil Nadu (7,673 ha). It is envisaged that spatial suitability demarcation even on this pilot scale will accelerate the expansion of sea cage farming in the country.

Introduction

Open sea cage farming in India was initiated in 2006 (Rao *et al*., 2013) during which, the sea cages were indigenously designed, developed and demonstrated by the Indian Council of Agricultural Research Central Marine Fisheries Research Institute (ICAR-CMFRI). Asian seabass (*Lates calcarifer*) was successfully farmed and harvested in a sea cage off the coast of Visakhapatnam, Bay of Bengal in 2007 (Rao *et al.*, 2013;

Mojjada, 2015). Since then, there have been several upgradation of the technology and its demonstration using different marine finfish and shellfish species along the Indian coast (Philipose *et al*., 2012). Sea cage farming is considered a low-impact farming practice with high economic returns when compared to pond-based fish farming (Rao *et al*., 2013; Aswathy *et al*., 2020). Consequently, the technology quickly attracted the attention of stakeholders and policymakers in the country. India with its 8,129 km coastline and 2.02 million km^2 of Exclusive Economic Zone (EEZ) offers tremendous scope for boosting marine fish production through sea cage farming. Understanding the importance of mariculture in food security and income generation, the Government of India has taken several initiatives to provide a greater boost to mariculture research and development (Gopalakrishnan and Imelda, 2015). Recognising the prospects offered by the sector, the Department of Fisheries, Government of India (DoF-GoI) and the National Fisheries Development Board (NFDB) entrusted ICAR-CMFRI to prepare the Draft National Mariculture Policy (NMP) for India in 2018 (Gopalakrishnan *et al*., 2019). The NMP underscored the urgent need to identify the most suitable locations along the Indian coast for sustainable intensification of mariculture activities such as sea cage culture, pen culture, seaweed culture and establishment of hatcheries and nurseries (Gopalakrishnan *et al*., 2019; Mojjada *et al*., 2021). Sea cage culture and seaweed farming were given priority by the Union Government, aligning with the national strategy to promote mariculture activities in a sustainable manner (Gopalakrishnan *et al*., 2019). Following this, a total of 23,970 ha area (317 locations) was identified as potential seaweed farming sites along the Indian coast (Johnson *et al*., 2020) with an estimated production potential of 9.58 million t wet weight year^{-1}.

Sea cage farming has been practised in several coastal regions in India such as Kerala (Imelda *et al*., 2010; Rao *et al*., 2010, 2013); Karnataka (Philipose *et al*., 2012, 2013); Gujarat (Mojjada *et al*., 2012a; Divu *et al*., 2018); Odisha (Mojjada *et al*., 2012b) and Andhra Pradesh (Ranjan *et al*., 2014). As of now, more than 3900 cage farming units have been functioning under the technical guidance of ICAR-CMFRI in different locations along the Indian coast. Selection of appropriate sites for sea cage farming has a major role in the success of cage farming and it is a vital necessity to enhance sustainable seafood production (Beveridge, 2004). Region-specific site selection, design, and operations are essential for successful cage culture practices (Loka *et al*., 2012). Proper site selection for marine cage culture can also influence capital costs, operating costs, fish growth, survival rates and fish production. Sea cages need to be deployed at locations with adequate water depth to optimise water exchange and maintain clearance from the bottom substrate during low tide (Chen and Chen, 2006; Corner *et al.,* 2006; Cho *et al*., 2012). Physical, chemical, and biological parameters can influence the efficacy of a sea cage farming system (Beveridge, 2004). Major water quality parameters, including temperature, dissolved oxygen, alkalinity, salinity, turbidity and concentrations of pollutants and other parameters like seasonal fluctuations in water volume, currents, rainfall, air temperature, wind speed and relative humidity can affect cage culture. Socio-economic characteristics that may be considered in cage culture include administrative regulations, competing resource uses, market conditions (*e.g.,* demand for fishery products and accessibility to markets), infrastructure support and availability of technical expertise. Moreover, prioritising such suitable areas for sea cage culture ensures sustainable development, which prevents conflict between resource users and reduces the chances of environmental contamination, improves the economic returns and viability of the farming system. Spatial information requirements for decision-makers in the context of aquaculture planning efforts can be effectively met through the utilisation of Geographical Information Systems (GIS) (Beveredge, 1996). Additionally, site selection criteria serve as a technical framework for the compilation of marine farming resource atlases, regulations, and legislations, which are essential for the mariculture development of the country (Rao *et al*., 2013). Given the non-uniform and uncertain topographical and oceanographic conditions prevalent along the maritime states of India, meticulous site selection for the installation of sea cages along the Indian coastline gains primary importance.

Multi-Criteria Evaluation (MCE) techniques and GIS-based site suitability models have been applied to identify suitable locations and also to support environmental decision-making and ecological planning (Stelzenmuller *et al*., 2017). GIS offers a suitable framework for applying spatial analytical tools and the MCE process facilitates diverse approaches to manage multi-criteria situations incorporating expert knowledge from the decision-makers (Carver, 1991). GIS-MCE tools have proven valuable in aquaculture for site selection across diverse culture systems and species, demonstrating their usefulness and adaptability for aquaculture planning, such as in Malaysia (Chor *et al*., 2022) and Tanzania (Mabula *et al*., 2023) for finfish farming and marine cage siting in Scotland (Hunter, 2009). In India, GIS-MCE-based modelling approach for identifying the best suitable mariculture sites along the north-eastern Arabian Sea has already been demonstrated by Divu *et al*. (2021). However, an extensive study for sea cage site selection for all the maritime states of the country has not been attempted yet. Considering the emerging scope of sea cage farming and as recommended in the NMP, we have adopted a preliminary geospatial approach to map the potential mariculture sites along the Indian coast, which will be useful for the development of initial action plans and policy development for cage-based mariculture activities. The data presented here is fairly indicative and the results are more exploratory than exclusive.

Materials and methods

The criteria taken into account for consideration when choosing sea cage locations include physical, chemical, biological parameters and topographical characteristics (Divu *et al.,* 2021). *In-situ* data on physical, chemical and biological factors of the marine environment, were assessed for considering site suitability. Chemical parameters were analysed using standard analytical procedures (APHA, 2005). Structural suitability of cage culture system for high-density polyethylene (HDPE) cage frames and low-cost galvanised iron (GI) cages (Rao *et al*., 2013) developed by ICAR-CMFRI were considered. The bench-marked suitability levels for the parameters were adopted from Divu *et al*. (2021) for arriving at the biological suitability and nutrient parameters limits for candidate species for marine cage culture. This study was restricted to identifying sites in nearshore waters, *i.e*., within 3 km of the shoreline, with depths of the areas ranging from 15-18 m. Prior to installation of cages, it is essential to ensure the availability of proper lease rights or legally valid authorisation to the users to carry out sea farming activities.

The site should be far from other uses, such as fishing, tourism, marine protected areas and navigational routes (Aswathy *et al*., 2020). So, for successful sea cagefarming, optimum levels of all the parameters need to be addressed before initiating sea cage farming.

The study identified various locations suitable for sea cage farming based on suitability criteria related to physico-chemical and topographic parameters based on peer-reviewed scientific reports (Imelda *et al*., 2010; Mohamed *et al*., 2010; Rao *et al*., 2010; Mojjada *et al*., 2012a, b, 2013, 2015; Ranjan *et al*., 2014; Divu *et al*., 2018). The water quality criteria were finalised (Table 1) considering the biological tolerance limits of the candidate marine finfish and shellfish species that are being cultured presently in India. The suitable locations were vectorised in a GIS platform and the potential area available for sea cage farming was calculated. The available area and the number of cage culture sites were plotted for easy visual identification using ArcGIS 10.8. The site suitability scheme developed by Divu *et al*. (2021) for spatial demarcation of location for sea cage farming is adopted here (Fig. 1).

Results

This preliminary study assessed the potential sites and estimated the area suitable for sea cage farming in nearshore waters along the maritime states of the country. The demarcated areas suitable for cage culture are spread over 134 locations in the 11 States and Union Territories (UTs) covering a total expanse of 46,958.2 ha. The potential sites along with their GPS coordinates are presented in Table 2. Additionally, details of the total number of sites/locations with available area (in ha) for each maritime state is presented in Table 3 and Fig. 2. Apart from these, details of state-wise locations, geo-referred boundaries (Table 2) and potential areas in each state were also estimated. The eastern coastal states comprising West Bengal, Odisha, Andhra Pradesh and Tamil Nadu collectively possess 88 potential mariculture sites for sea cage farming, accounting for 21,518 ha area (Table 3; Fig. 3). The western coastal states, including two UTs possess 46 sites with an estimated area over 25,305 ha (Table 3; Fig. 4). Nearshore waters of Andhra Pradesh ranked top among the maritime states with 11,792 ha for potential cage culture, whereas Gujarat topped among the west coast states, having 11,572.2 ha (Table 3). The top 3 coastal states having the highest potential area for sea cage farming in the country are Andhra Pradesh, Gujarat and Tamil Nadu. Based on an estimated carrying capacity of 15 cages of 6 m diameter ha^{-1} and production potential of 3 t $cage^{-1}$ yr^{-1} (Joseph, 2009), a potential mariculture production of 2.11 million t yr^{-1} is possible from the identified areas (46,958.2 ha).

Table 1. Water quality parameters and their ranges considered for the suitability assessment

Parameter	Suitable range
Temperature	27–31.5°C
Salinity	27–37 ppt
Dissolved oxygen	> 4 ppm
Hydrogen ion index (pH)	7.0–8.5
Ammonia-nitrogen (NH_3-N)	< 0.5 ppm
Nitrate (NO_3-N)	< 200 mg l^{-1}
Nitrite (NO_2-N)	< 4 mg l^{-1}
Phosphate	< 70 mg l^{-1}

(Adopted and modified from FAO, 1988 UNDP/FAO Regional Sea Farming Development and Demonstration Project, RAS/86/024.)

Discussion

Identifying suitable and productive sites for sea cage farming is important for the environmental sustainability and economic viability as it considers issues and helps resolve conflicts between users at the planning stage, thereby enabling rational usage of the available coastal space. Several authors have reviewed GIS systems (Burrough, 1986; Aranoff, 1989) as one of the best tools for marking boundaries and various decision-making processes. According to Burrough (1986), GIS can be used as a tool to prepare Database Management System (DBMS) that enables users to store, retrieve and change data integrated with a series of routines which allow sophisticated spatial analysis and display. Several investigations were carried out on GIS approach for sustainable aquaculture

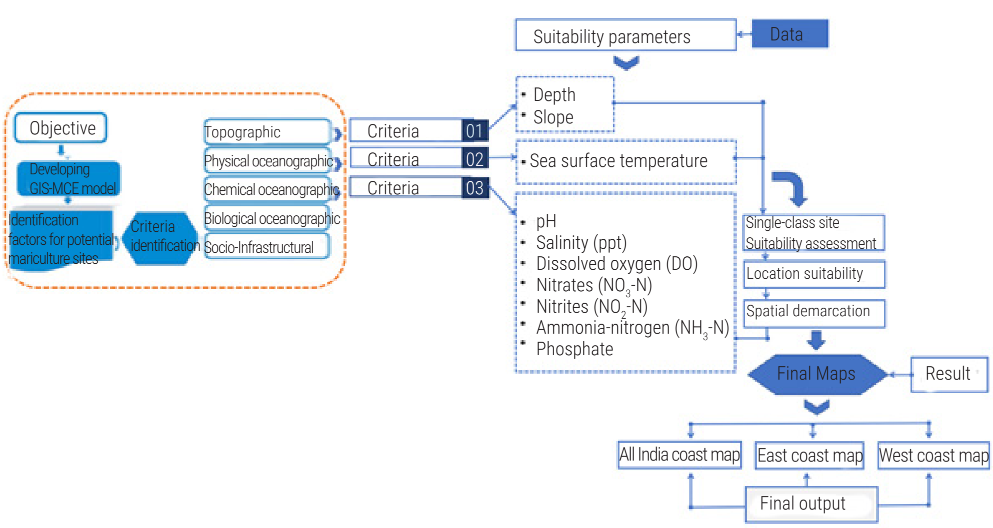

Fig.1. Optimised and modified site suitability schema for spatial demarcation of potential cage farming locations along the Indian coast (Source: Divu *et al.*, 2021)

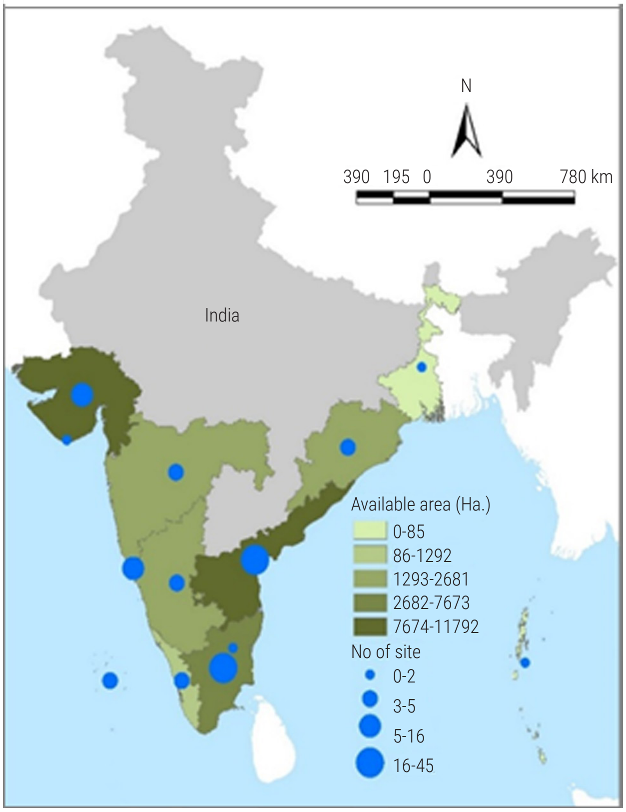

Fig. 2. State-wise range of available area suitable for cage farming spread across the Indian coastline

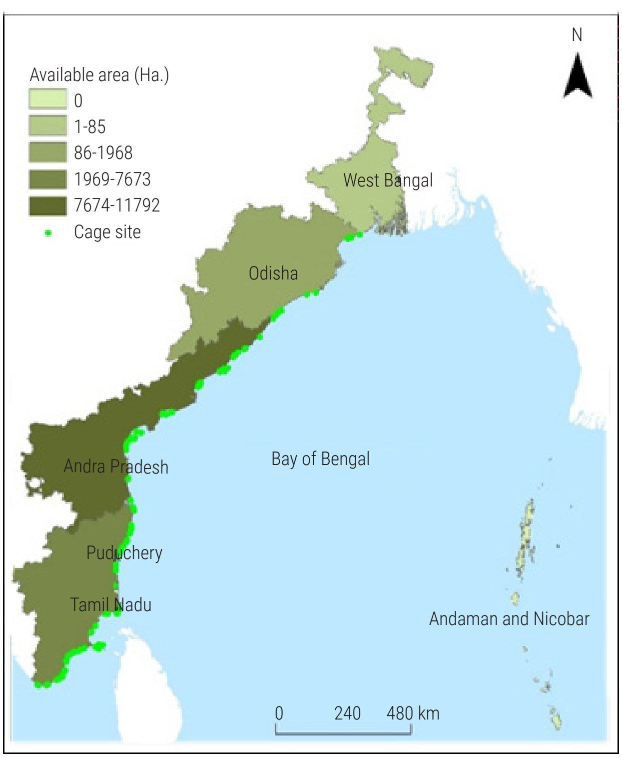

Fig. 3. Potential sea cage farming sites spread across the eastern coastal states of India

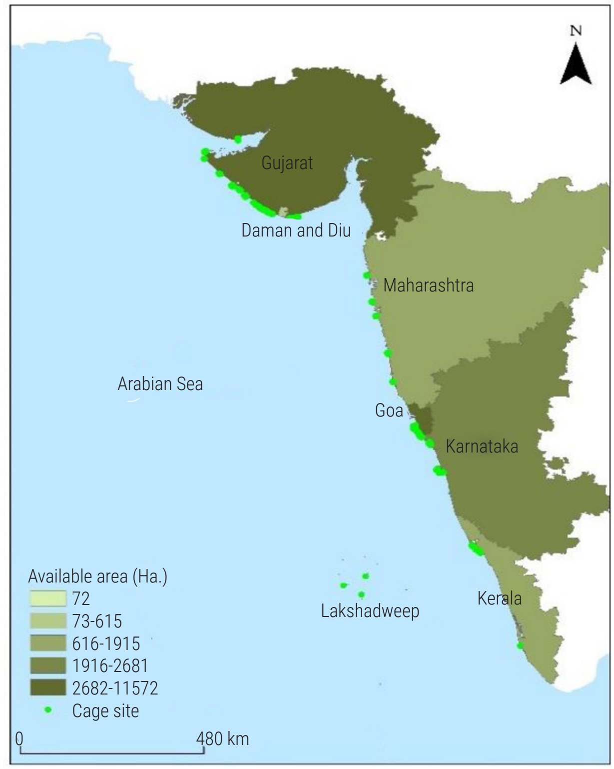

Fig. 4. Potential sea cage farming sites spread across western coastal states of India

area management especially site selection. A classic example is the study performed on the demarcation of the most suitable and sustainable locations within the Bay of Plenty, New Zealand by analysing the availability of natural conditions as well as physical and chemical parameters (Longdill *et al.,* 2008). Site selection for salmonid cage culture development in Scotland was assessed using GIS tool by using the data on bathymetry, current, shelter and water quality to determine the suitability of the site for cage culture (Ross *et al.,* 1993).

The present study aimed to facilitate and accelerate the cage farming practices promoted through the implementation of PMMSY schemes of the Government of India by the concerned maritime states. This preliminary assessment based on published literature has identified 134 sites that were found suitable for sea cage farming spanning nine maritime states and two union territories, accounting for a total area of 46,958.2 ha. The research highlighted the maximum suitable area for cage farming along the Andhra Pradesh coast (11,792 ha.), followed by Gujarat (11,572.2 ha) and Tamil Nadu (7,673 ha) and it underscores the regional disparities in the potential for aquaculture development. In Andhra Pradesh, cage farming of marine finfishes in the coastal waters has been gaining popularity due to various successful farmer participatory demonstrations carried out by ICAR-CMFRI under different schemes (Megarajan *et al.,* 2021). Cage farming of cobia, pompano, lobsters and seabass is gaining popularity in the state of Tamil Nadu (Gopakumar, 2013; Johnson *et al.,* 2019). Integrated Multi-Trophic Aquaculture (IMTA) activities by incorporating seaweeds or molluscs along with cage farming are also widely practised

Table 2. Details of 134 potential sea cage farming sites subjected to preliminary assessment across Indian maritime states

Name of the State	Site	Location	Geo boundary	GPS Coordinates (DD)	
				E	N
West Bengal	1	Digha (Purba Medinipur)	1	87.537258	21.581762
			2	87.546198	21.585162
			3	87.548543	21.577863
			4	87.540574	21.575090
Odisha	1	Chandrabhaga	1	86.127450	19.844536
			2	86.123553	19.852186
			3	86.140363	19.856311
			4	86.142944	19.848716
	2	Pentakota	1	85.858616	19.786945
			2	85.869558	19.790612
			3	85.872514	19.784552
			4	85.861258	19.780941
	3	Dagra	1	87.277602	21.508501
			2	87.293770	21.508259
			3	87.292732	21.497273
			4	87.276571	21.497990
	4	Chawmukh	1	87.224029	21.504759
			2	87.222332	21.494719
			3	87.248537	21.493116
			4	87.248918	21.503310
	5	Bahabalpur	1	87.136771	21.465427
			2	87.138536	21.457199
			3	87.163477	21.457920
			4	87.163831	21.466769
	6	Sonepur (inflow area)	1	84.787616	19.061911
			2	84.793199	19.059600
			3	84.803744	19.067199
			4	84.799330	19.071296
	7	Ramayyapatnam	1	84.845745	19.151928
			2	84.854620	19.142955
			3	84.843892	19.135347
	8	Gopalpur	1	84.918685	19.236992
			2	84.924753	19.231826
			3	84.936343	19.242242
			4	84.931283	19.247069
	9	Argipalli	1	85.018349	19.301980
			2	85.032360	19.288304
			3	85.057738	19.304615
			4	85.049143	19.318749
Andhra Pradesh	1	Baruva	1	84.349451	18.525438
			2	84.361524	18.538259
			3	84.372389	18.530818
			4	84.360557	18.517540
	2	Kocherla	1	83.570128	17.988586
			2	83.587884	18.005418
			3	83.595986	18.000356
			4	83.579038	17.981835
	3	Koyyam	1	83.853848	18.158330
			2	83.876977	18.169093
			3	83.883115	18.160809
			4	83.860992	18.150073
	4	D. Machilesam	1	83.889432	18.176440
			2	83.914593	18.190119
			3	83.922031	18.181344
			4	83.8984631	18.170266
	5	Dibbalapalem (tentative location) Chintapalli Village	1	83.648731	18.047600
			2	83.665065	18.062820
			3	83.672636	18.057210
			4	87.163831	21.466769

6	Chintapalli (Annavaram)	1	83.510657	17.917990
		2	83.529424	17.932218
		3	83.535739	17.924296
		4	83.516685	17.911172
7	Mukkam	1	83.334715	17.591301
		2	83.346707	17.606269
		3	83.357758	17.599891
		4	83.345915	17.584182
8	Jalaripeta	1	83.070879	17.490003
		2	83.091378	17.500999
		3	83.104171	17.487480
		4	83.083830	17.475100
9	Mangamaripeta	1	83.220230	17.585183
		2	83.227340	17.578158
		3	83.205582	17.559456
		4	83.195610	17.567408
10	Bheemili	1	83.244254	17.511617
		2	83.263671	17.500934
		3	83.253433	17.488010
		4	83.235481	17.497956
11	Pampodipeta	1	82.449610	17.127527
		2	82.463315	17.119395
		3	82.447117	17.103242
		4	82.433185	17.111764
12	Uppada	1	82.395615	17.038386
		2	82.409317	17.030919
		3	82.396298	17.016399
		4	82.381883	17.028215
13	Konapapapeta	1	82.446840	17.069441
		2	82.461424	17.063297
		3	82.454187	17.049929
		4	82.438474	17.057948
14	Danaiahpeta	1	82.488156	17.160668
		2	82.501096	17.153179
		3	82.480360	17.139195
		4	82.473347	17.146657
15	Perumallapuram	1	82.476542	17.175797
		2	82.485455	17.169761
		3	82.466029	17.151691
		4	82.456933	17.160584
16	Chodipallipeta	1	82.436644	17.143505
		2	82.444244	17.137571
		3	82.430410	17.127612
		4	82.422503	17.134098
17	Vemuladeevi	1	81 368012	16.213027
		2	81.372303	16.191938
		3	81.350228	16.191717
		4	81.346429	16.208593
18	Perupalem	1	81.552797	16.274432
		2	81.583605	16.274433
		3	81.584721	16.261137
		4	81.556505	16.264353

	19	Etimoga	1	80.564103	15.654097
			2	80.595670	15.666749
			3	80.600545	15.657175
			4	80.570127	15.642928
	20	Nagayalanka	1	80.449219	15.699855
			2	80.458858	15.684985
			3	80.434161	15.671030
			4	80.423534	15.684749
	21	Kruthivennu	1	81.258439	16.219302
			2	81.266611	16.215115
			3	81.256855	16.197022
			4	81.246546	16.201778
	22	Urlagondadibba	1	81.274680	16.246193
			2	81285825E	16.238134
			3	81.271295	16.219891
			4	81.259688	16.227069
	23	Chinnagollapalem	1	81.433527	16.225212
			2	81.434574	16.213978
			3	81.403757	16.211301
			4	81.402311	16.219367
	24	Nizampatnam	1	80.399788	15.498891
			2	80.401782	15.487938
			3	80.362300	15.483838
			4	80.359114	15.493407
	25	Suryalanka	1	80.304528	15.514570
			2	80.315429	15.505712
			3	80.305574	15.488989
			4	80.291271	15.495873
	26	Vaadarevu	1	80.240647	15.494716
			2	80.257237	15.485994
			3	80.247589	15.470881
			4	80.231302	15.477566
	27	Peddaganjam	1	80.157411	15.397123
			2	80.170250	15.391497
			3	80.155078	15.366879
			4	80.142823	15.373911
	28	Ammanabrolu	1	80.122980	15.338363
			2	80.134493	15.332966
			3	80.129538	15.313690
			4	80.115627	15.317390
	29	Kothapalem	1	80.100767	15.277218
			2	80.112645	15.274424
			3	80.108155	15.244800
			4	80.095554	15.247733
	30	Pakala	1	80.256937	13.651628
			2	80.262958	13.622540
			3	80.254599	13.620073
			4	80.248122	13.643655
	31	Karedu	1	80.119758	15.150950
			2	80.130715	15.147633
			3	80.124051	15.132489
			4	80.113913	15.134216
	32	Mypadu	1	80.174181	14.305348
			2	80.184936	14.302660
			3	80.180059	14.284688
			4	80.167535	14.289697
	33	Krishnapatnam	1	80.166189	14.286416
			2	80.180146	14.281269
			3	80.174244	14.262670
			4	80.159474	14.267628
Tamil Nadu	1	Olaikuda	1	79.368681	9.306924
			2	79.376380	9.309425

		3	79.374103	9.315832
		4	76.364988	9.314565
2	Thangachimadom	1	79.232976	9.313936
		2	79.254962	9.322940
		3	79.250024	9.331357
		4	79.231023	9.322204
3	Pamban	1	79.232613	9.194331
		2	79.242782	9.190953
		3	79.249954	9.201300
		4	79.238716	9.202792
4	Mandapam	1	79.120918	9.253678
		2	79.126517	9.244222
		3	79.142319	9.249740
		4	79.141128	9.258668
5	Naripayur South	1	78.434066	9.097824
		2	78.458286	9.103866
		3	78.438656	9.083725
		4	78.466954	9.092028
6	Kannirajapuram	1	78.407131	9.086497
		2	78.421622	9.091352
		3	78.424395	9.082395
		4	78.410784	9.078288
7	Valinokkam	1	78.648957	9.176933
		2	78.650438	9.175367
		3	78.652955	9.175903
		4	78.651648	9.178853
8	Keelamunthal	1	78.600803	9.129468
		2	78.613100	9.122183
		3	78.626021	9.128602
		4	78.620479	9.135279
9	Keelakarai	1	78.778071	9.215910
		2	78.778635	9.213378
		3	78.786832	9.214552
		4	78.786640	9.217364
10	Muthupettai	1	79.411860	10.248575
		2	79.524516	10.230234
		3	79.544732	10.260658
		4	79.4157699	10.276111
11	Sippikulam	1	78.253252	8.978119
		2	78.261123	8.971043
		3	78.257516	8.976562
		4	78.268232	8.986325
12	Sippikulam	1	78.298367	9.014577
		2	78.313872	8.999035
		3	78.263662	8.965447
		4	78.251633	8.979160
13	Kayalpatinam	1	78.148889	8.560924
		2	78.170740	8.560227
		3	78.165230	8.526363
		4	78.143446	8.528039
14	Periyathalai	1	77.999274	8.327146
		2	78.009974	8.317135
		3	77.975926	8.291916
		4	77.962890	8.307509
15	Kulasekarapatinam	1	78.080562	8.421719
		2	78.100849	8.415424
		3	78.088949	8.382045
		4	78.067969	8.388963
16	Manapad	1	78.084557	8.369272
		2	78.098958	8.349745
		3	78.051220	8.334177
		4	78.042418	8.351591

17	Veerapandianpatinam	1	78.149366	8.560135
		2	78.172028	8.557438
		3	78.166666	8.523851
		4	78.144441	8.526269
18	Alangarthattu	1	78.171573	8.830440
		2	78.194354	8.839956
		3	78.217979	8.812233
		4	78.190027	8.806510
19	Kootapuli	1	77.626474	8.142889
		2	77.630530	8.129764
		3	77.600498	8.124494
		4	77.598875	8.135119
20	Muttom	1	77.279326	8.134344
		2	77.330661	8.104140
		3	77.319653	8.087858
		4	77.273888	8.125282
21	Arokyapuram	1	77.593688	8.130596
		2	77.605079	8.116551
22	Chinnamuttom	3	77.582116	8.097017
		4	77.571918	8.109094
23	Kooduthalai	1	77.955846	8.303525
		2	77.967163	8.287543
		3	77.932706	8.268270
		4	77.919723	8.280788
24	Uvari	1	77.912013	8.274570
		2	77.918338	8.268495
		3	77.889129	8.249347
		4	77.881780	8.255606
25	Arasanagiripatinam	1	79.141259	9.894166
		2	79.151351	9.889654
		3	79.138026	9.868710
		4	79.129565	9.873185
26	Puthupatinam	1	79.014933	9.713767
		2	79.024483	9.708549
		3	78.991634	9.663809
		4	78.981669	9.669540
27	Vedaranyam	1	79.879533	10.398544
		2	79.898292	10.399171
		3	79.905236	10.365629
		4	79.885191	10.365015
28	Kodiakarai	1	79.803401	10.255388
		2	79.847110	10.254780
		3	79.850201	10.241795
		4	79.802990	10.242404
29	Pushpavanam	1	79.874887	10.470485
		2	79.882390	10.468552
		3	79.884592	10.447020
		4	79.876201	10.447081
30	Sonankuppamand Singarathope	1	79.789364	11.731658
		2	79.796383	11.731051
		3	79.794798	11.713307
		4	79.784606	11.713605
31	Rajapettai	1	79.777230	11.690544
		2	79.788823	11.689950
		3	79.780970	11.657504
		4	79.769722	11.659732
32	Chithiraipettai	1	79.768836	11.08177
		2	79.781038	11.650036
		3	79.774780	11.552449
		4	79.763978	11.549760
33	Thamanampettai	1	79.768836	11.081751
		2	79.781038	11.650036

			3	79.782414	11.525813
			4	79.769514	11.527454
	34	Bommayapalayam	1	79.853177	11.992345
			2	79.855936	11.991302
			3	79.852515	11.984244
			4	79.850055	11.985655
	35	Koonimedu	1	79.908948	12.099818
			2	79.917478	12.095943
			3	79.894155	12.057297
			4	79.886212	12.062404
	36	Anumandai	1	79.937695	12.141432
			2	79.951079	12.135372
			3	79.928637	12.101188
			4	79.917086	12.108297
	37	Ekkiyarkuppam	1	79.977759	12.199217
			2	79.993439	12.189930
			3	79.962078	12.141601
			4	79.946254	12.151324
	38	Edaikazhinadu	1	80.021839	12.274190
			2	80.034300	12.265132
			3	80.133034	12.387368
			4	80.116686	12.398314
	39	Kadalur Chinnakuppam and Kadalur Periyakuppam	1	80.151720	12.456214
			2	80.159105	12.452433
			3	80.148196	12.427235
			4	80.137373	12.434371
	40	Devaneri	1	80.222420	12.660261
			2	80.234447	12.656445
			3	80.224043	12.628897
			4	80.211651	12.633586
	41	Semencheri	1	80.256343	12.767974
			2	80.264616	12.765993
			3	80.249407	12.711979
			4	80.237917	12.715811
	42	Kovalam	1	80.278197	12.803732
			2	80.299444	12.802522
			3	80.290249	12.769859
			4	80.269492	12.771709
	43	Kanathur	1	80.268189	12.897686
			2	80.287911	12.900589
			3	80.281142	12.850875
			4	80.263470	12.852079
	44	Kalanji	1	80.350359	13.358679
			2	80.370910	13.359595
			3	80.372370	13.323474
			4	80.350912	13.320884
	45	Pulicut	1	80.331227	13.430848
			2	80.344221	13.432832
			3	80.354946	13.384437
			4	80.339921	13.383157
Kerala	1	Edakkad	1	75.410288	11.795142
			2	75.418770	11.799416
			3	75.433306	11.784947
			4	75.431368	11.776406
	2	Ayikkara Fort	1	75.359207	11.846630
			2	75.358447	11.838519
			3	75.369124	11.835079
			4	75.370642	11.842433
	3	Neerkadavu	1	75.310023	11.889288
			2	75.320953	11.869315
			3	75.332631	11.875001
			4	75.321375	11.895036

	4	Puthiyangadi	1	75.219720	11.982643
			2	75.241337	11.959785
			3	75.254004	11.971972
			4	75.232830	11.994394
Karnataka	1	Kheni	1	74.246016	14.678463
			2	74.260573	14.679468
			3	74.262476	14.651676
			4	74.247739	14.650153
	2	Bellikeri	1	74.203099	14.698426
			2	74.229389	14.677366
			3	74.238613	14.690079
			4	74.219973	14.705639
	3	Mudga	1	74.217344	14.717601
			2	74.237230	14.728872
			3	74.240380	14.723190
			4	74.223752	14.711729
	4	Hadin	1	74.536324	13.931356
			2	74.551723	13.935362
			3	74.565777	13.921056
			4	74.551307	13.916450
	5	Belake	1	74.457992	13.904414
			2	74.530254	13.921421
			3	74.417292	14.028946
			4	74.386680	13.989267
Goa	1	Polem-1	1	74.042008	14.882364
			2	74.059836	14.860989
			3	74.045594	14.847986
			4	74.027300	14.868764
	2	Polem-2	1	73.997672	14.927864
			2	74.014833	14.903369
			3	73.997856	14.894328
			4	73.979258	14.916703
	3	Canacona-1	1	73.969264	14.976719
			2	73.989111	14.955944
			3	73.975431	14.941567
			4	73.955939	14.962508
	4	Canacona-2	1	73.942189	15.022664
			2	73.960144	15.001872
			3	73.948367	14.987636
			4	73.929747	15.007928
	5	Cola-1	1	73.900364	15.074142
			2	73.924981	15.059469
			3	73.911042	15.047658
			4	73.886614	15.062228
	6	Cola-2	1	73.881572	15.121861
			2	73.900147	15.119853
			3	73.893344	15.092531
			4	73.875275	15.096047
	7	Votorinim Beach-1	1	73.852808	15.086878
			2	73.880164	15.090306
			3	73.882036	15.073272
			4	73.854664	15.071319
	8	Cola-3	1	73.926844	15.050408
			2	73.938822	15.036283
			3	73.911606	15.021397
			4	73.898681	15.033039
	9	Polem-3	1	74.019628	14.899483
			2	74.031242	14.885103
			3	74.009250	14.874903
			4	73.995550	14.885633
	10	Cananguinim Beach-2	1	73.907381	15.177675
			2	73.904558	15.151517

			3	73.885725	15.153003
			4	73.904558	15.151517
	11	Cananguinim Beach-3	1	73.844636	15.156786
			2	73.864442	15.156761
			3	73.863333	15.129703
			4	73.844811	15.131586
Maharashtra	1	Achira	1	72.744042	19.140369
			2	72.759003	19.139364
			3	72.757935	19.159870
			4	72.743682	19.160209
	2	Shrivardhan (Very near to shore 0.3 km)	1	72.965511	18.055407
			2	72.976599	18.054873
			3	72.979035	18.078610
			4	72.964378	18.078795
	3	Kunkeshwar	1	73.362493	16.328003
			2	73.371560	16.304361
			3	73.382583	16.306778
			4	73.374480	16.330258
	4	Shirgav	1	73.231658	17.094760
			2	73.250537	17.062667
			3	73.265254	17.069657
			4	73.249301	17.101849
	5	Kashid	1	72.879162	18.432416
			2	72.888549	18.435796
			3	72.880291	18.457212
			4	72.870174	18.453840
Gujarat	1	Sutrapada	1	70.433925	20.839166
			2	70.419489	20.824433
			3	70.462703	20.799250
			4	70.476458	20.814308
	2	Veraval	1	70.385380	20.883793
			2	70.383281	20.877374
			3	70.393682	20.871950
			4	70.396623	20.876802
	3	Dari	1	70.247633	20.928782
			2	70.291905	20.896778
			3	70.306169	20.911841
			4	70.263848	20.946709
	4	Prashanwada	1	70.497361	20.790194
			2	70.507214	20.799750
			3	70.542603	20.782413
			4	70.532353	20.774240
	5	Mangrol	1	70.083731	21.082561
			2	70.090851	21.088904
			3	70.110276	21.073556
			4	70.102980	21.067015
	6	Simar	1	70.225343	20.959153
			2	70.238046	20.949385
			3	70.247262	20.956808
			4	70.232769	20.967477
	7	Navabandar	1	71.105168	20.709018
			2	71.116784	20.694152
			3	71.147969	20.701583
			4	71.136963	20.717309
	8	Jhaleshwar	1	70.326399	20.896232
			2	70.338454	20.900392
			3	70.348606	20.890690
			4	70.336166	20.884301
	9	Chorwad	1	70.154166	21.012150
			2	70.190119	20.987288
			3	70.204184	20.995355
			4	70.167777	21.023316

	10	Miyani	1	69.273256	21.864762
			2	69.291739	21.831157
			3	69.313466	21.836879
			4	69.285578	21.867112
	11	Navibandar	1	69.738971	21.431692
			2	69.766801	21.401689
			3	69.787419	21.408035
			4	69.757815	21.439509
	12	Porbandar	1	69.563480	21.537644
			2	69.594096	21.503614
			3	69.626195	21.518189
			4	69.588876	21.554998
	13	Madhavpur	1	69.866636	21.266888
			2	69.899404	21.288245
			3	69.932078	21.248917
			4	69.899591	21.227950
	14	Mundra	1	69.727740	22.727740
			2	69.728470	22.794249
			3	69.728490	22.792585
			4	69.727687	22.793258
	15	Mithapur	1	68.932430	22.424896
			2	68.949239	22.416311
			3	68.978493	22.450278
			4	68.958574	22.457648
	16	Dwarka	1	68.925301	22.248557
			2	68.933420	22.252120
			3	68.938637	22.240301
			4	68.931522	22.238971
Diu	1	Diu-1	1	71.007739	20.680190
			2	71.027924	20.691034
			3	71.035515	20.684739
			4	71.020052	20.670142
	2	Diu-2	1	70.939611	20.678067
			2	70.940864	20.661732
			3	70.968190	20.662925
			4	70.966418	20.678193
Lakshadweep Islands	1	Amini	1	72.726114	11.117220
			2	72.730191	11.114155
			3	72.735167	11.121017
			4	72.730595	11.123459
	2	Agatti	1	72.198655	10.860457
			2	72.201664	10.859458
			3	72.195716	10.848911
			4	72.192550	10.850828
	3	Kavartti	1	72.629865	10.563293
			2	72.631738	10.562073
			3	72.624963	10.551849
			4	72.622803	10.552738

here (Johnson, 2018). Through this study, more suitable areas for cage farming were identified along the Tamil Nadu coast. The only one site identified for the West Bengal coast, points to substantial challenges linked to the coastal topography, terrain characteristics and dynamics of two major rivers in that particular region. Basically, this investigation serves as a foundational baseline for future endeavours in cage culture site selection along the Indian coast.

Spatial modelling offers an accurate and integrated approach than conventional analytical and map-making techniques (Mooneyhan, 1985). In the context of cage aquaculture, GIS-based models have been successfully demonstrated for site selection of offshore marine floating fish cage aquaculture in Tenerife, Canary Islands (Perez *et al.,* 2005). In the Indian scenario, a decision-making framework has been developed for identifying the best suitable mariculture sites in Gujarat State using GIS-MCE-based modelling (Divu *et al.,* 2021). In that study it was found that of the demarcated area, 27.43% as the most suitable and 25% as moderately suitable for mariculture development, emphasising the untapped potential of the available open waters of Gujarat state. A similar study in Taiwan (Wu *et al.,* 2020) elucidated relationships between SST, wind speed and cumulative duration of wind during extreme events. The present study analysed various physico-chemical parameters including temperature, salinity, pH and nutrients, along with biological parameters, for assessment of the region-specific site suitability along the Indian coastline.

Table 3. Total number of potential sites and total available area for sea cage farming in each maritime state of India

State/UT	Total no. of sites	Location and available area (in ha.) in each site					Total available area (ha) in each site
West Bengal	1	1. Digha (Purba Medinipur)-85	-	-	-	-	85
Odisha	9	1.Chandrabhaga-165	2.Pentakota-85	3.Dagra-180	4.Chawmukh-270	5.Bahabalpur-228	1,968
		6.Sonepur (inflow area) - 60	7. Ramayyapatnam-200	8.Gopalpur-140	9.Argipalli - 650	-	
Andhra Pradesh	33	1.Baruva-280	2.Kocherla-320	3.Koyyam-300	4.D Machilesam-355	5.Dibbalapalem-250	11,792
		6.Chintapalli-265	7.Mukkam-300	8.Konapapapeta-240	9.Danaiahpeta-310	10.Perumallapuram-340	
		11.Pampodipeta-412	12.Uppada-380	13.Jalaripeta-520	14.Mangamaripeta-400	15.Bheemili-350	
		16.Chodipallipeta-190	17.Vemuladeevi-491	18.Perupalem-360	19.Etimoga-440	20.Nagayalanka-620	
		21.Kruthivennu-250	22.Urlagondadibba-380	23.Chinnagollapalem-375	24.Nizampatnam-509	25.Suryalanka-390	
		26.Vaadarevu-400	27.Peddaganjam-460	28.Ammanabrolu-330	29.Kothapalem-435	30.Pakala-325	
		31.Karedu-200	32.Mypadu-255	33.Krishnapatnam-360	-	-	
Tamil Nadu	45	1.Olaikuda-77	2.Thangachimadom-100	3.Pamban-48	4.Mandapam-235	5.Naripayur South-180	7,673
		6.Kannirajapuram-75	7.Valinokkam-11	8.Keelamunthal-210	9.Keelakarai-27	10.Muthupettai-185	
		11.Sippikulam-225	12.Sippikulam-422	13.Kayalpatinam-241	14.Periyathalai-320	15.Kulasekarapatinam-210	
		16.Manapad-345	17.Veerapandianpatinam-241	18.Alangarthattu-280	19.Kootapuli-165	20.Muttom-115	
		21.Arokyapuram-122	22.Chinnamuttom-122	23.Kooduthalai-125	24.Uvari-180	25.Arasanagiripatinam-145	
		26.Puthupatinam-166	27.Vedaranyam-277	28.Kodiakarai-317	29.Pushpavanam-136	30.Sonankuppamand Singarathope-100	
		31.Rajapettai-151	32.Chithiraipettai-275	33.Thamanampettai-151	34.Bommayapalayam-27	35.Koonimedu-111	
		36.Anumandai-184	37.Ekkiyarkuppam-294	38.Edaikazhinadu-94	39.Kadalur, Kadalur Periyakuppam-139	40.Devaneri-160	
		41.Semencheri-100	42.Kovalam-140	43.Kanathur-154	44.Kalanji-133	45.Pulicut-280	
Kerala	4	1.Edakkad-220	2.Ayikkara Fort-120	3.Neerkadavu-340	4.Puthiyangadi-612	-	1,292
Karnataka	5	1.Kheni-425	2.Bellikeri-480	3.Mudga-213	4.Hadin-323	5.Belake-1240	2,681
Goa	11	1.Polem-1-676	2.Polem-2-711	3.Canacona-1-651	4.Canacona-2-668	5.Cola-1-641	7,230
		6.Cola-2-560	7.Cananguinim Beach-1-612	8.Cola-3-588	9.Polem-3-722	10.Cananguinim Beach-2-689	
		11.Cananguinim Beach-3-712	-	-	-	-	
Maharashtra	5	1.Achira-289	2.Shrivardhan-340	3.Kunkeshwar-300	4.Shirgav-720	5.Kashid-266	1,915
Gujarat	16	1.Sutrapada-1115	2.Veraval-120	3.Dari-1220	4.Prashanwada-590	5.Mangrol-210	11,572.2
		6.Simar-200	7.Navabandar-465	8.Jhaleshwar-226	9.Chorwad-860	10.Miyani-735	
		11.Navibandar-1000	12.Porbandar-1650	13.Madhavpur-2260	14.Mundra-1.2	15.Mithapur-820	
		16.Dwarka-100					
Diu	2	1.Diu-1-280	2.Diu-2-335	-	-	-	615
Lakshadweep	3	1.Amini-51	2.Agatti-49	3.Kavaratti-35	-	-	135
Total Sites	**134**					**Total Area (in ha) -**	**46,958.2**

In India, the state of Gujarat has the longest coastline (1,600 km) which is approximately 23% of the country's total mainland coastline. Andhra Pradesh has the second-longest mainland coastline with a total length of 974 km. m. Considering all the parameters for cage culture suitability, Andhra Pradesh has the highest available area for sea cage farming. These two states in the country can play a key role in substantial marine fish production through mariculture in the territorial waters. A robust spatial planning, territorial water governance mechanisms and socially acceptable policy framework are essential for the future development of this sector. The GIS-based Multi-Criteria Evaluation (MCE) model developed for the Gujarat coast (Divu *et al*., 2021) can be considered for all other maritime states of the country for modelling the territorial sea space with their region-specific criteria integration. It must be noted that the geo-referenced data presented here must be validated before any commercial venture and it is also advised that the sites must be re-investigated with the inclusion of additional suitability parameters as suggested by various researchers (Radiarta *et al.,* 2008; Gimpel *et al.,* 2015).

Site suitability indices may vary in future modelling exercises due to integrating additional region-specific benchmarking parameters. Studies on mariculture site selection have shown the effectiveness of GIS in aiding regulatory authorities for implementation, environmental control and assessing overall carrying capacity for sustainable marine cage farming. Criteria for site selection must be addressed before mass-scale initiation in various developmental schemes, expanding to existing demarcated locations.

The results of this study aimed to present a comprehensive view on the availability of possible potential sea cage farming sites available in a primary level in a pan India manner. However, the present study was carried out for nearshore waters only (within 3 km of the coastline) with limited site selection parameters to arrive at a preliminary picture to the respective maritime states for availing the assessed sites for their immediate use. Furthermore, mariculture activities conducted by ICAR-CMFRI under various projects, technology transfer, and frontline demonstrations along various maritime locations of the country were also consulted for this study. Nevertheless, the study is non-comprehensive in some aspects of scientific site selection to include all possible locations along the territorial boundaries of the respective maritime states. In future, detailed modelling exercises by adding more site suitability parameters along with validation is crucial for facilitating the sustainable expansion of mariculture in open waters of the country. India has a vast expanse of ocean space beyond the 20 m depth zone which can be utilised for expanding offshore mariculture. Large floating and/or submersible cages of >20 m dia. on an industrial scale is being mooted as a means of increasing mariculture production from offshore areas. While India is looking to expanding mariculture to offshore regions in the future, leveraging advanced modelling techniques for effective offshore site selection is paramount. The modelling exercise undertaken by Divu *et al.,* in 2021 could be used as a tool. To optimise its application in offshore site selection, the model can be adapted as a practical region/site specific recommendation of the offshore culture system. Use of *in-situ* data from data buoys through collaborative arrangements with national agencies would ensure that additional factors such as water temperature, nutrient levels, ocean currents, and ecological characteristics can be included to enhance the model's precision in reflecting the complex dynamics of offshore environments. Techno-economic, ecological and socio-economic catastrophes are most likely to occur in the coastal region if we are not adopting a holistic approach for mariculture implementation. Therefore, the Union government and state administrations must draw an action plan for developing sustainable spatial plans and territorial water governance plans in consultation with R&D organisations and stakeholders.

In view of emerging importance for site suitability and to facilitate efficient allocation of sites to stakeholders by respective state government departments, we provide a few recommendations for preliminary expansion of seacage farming in Indian coastal states. Foremost, before embarking on large-scale commercial ventures, a thorough, case-by-case site examination is strongly recommended. This entails a detailed spatial analysis incorporating diverse factors such as physical, biological and socio-political considerations, mapped on a GIS platform to ensure a well-informed approach to site selection. Additionally, due emphasis should be given to the carrying capacity of the each selected site, including impact on benthic flora and fauna. In situations where the cage sites are close to coastal community settlements, discussions and dialogues with coastal residents are essential before operating cages from these locations. So, the involvement of coastal communities in sea cage farming activities is very essential. Government agencies may be encouraged to support the farmers by way of providing financial assistance in procuring infrastructure for farm operations like boats, safety and rescue measures, along with other required inputs. Cage culture clusters comprising batteries of 50/100 cages, along with necessary farm infrastructure, can be developed for each region on a pilot scale. Following that, critical inputs such as seed, feed and community coordination must be channelised for the farming operations. More awareness campaigns must be carried out with the active participation of coastal communities. Since sea space has open access to it, with diverse maritime stakeholders like conventional fishing, motorised vessels, shipping, navigation, defense, sea routes as well as oil, gas fields, there is a crucial need for comprehensive spatial policy for sustainable sea cage mariculture. This policy is essential for ecologically sound, socially acceptable and conflict-free territorial water usage, allowing efficient governance and maximising economic and social benefits. Technology, stakeholders and policy must be integrated through coordination and timely communication with necessary backup plans. A first step in the country has been brought in this direction by the state of Goa which has brought out a leasing policy in its Goa State Mariculture Policy 2020 (Govt. of Goa, 2020). Apart from this, it is also strongly recommended to have a plan of action, designed in a scientific and socially fitting manner through consultations and all necessary approvals must be obtained in time for the successful sea cage farming adoption and implementation along the coastal states at a large scale.

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Declaration of generative AI in scientific writing

During the preparation of this work, the author(s) used AI-assisted technologies to improve the readability and language of the manuscript during the writing process. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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