International Symposium

MECOS 4

Marine Ecosystems Challenges and Opportunities

4-6 November 2025

ICAR-CMFRI, Kochi

MBAI
The Marine Biological Association of India

Souvenir

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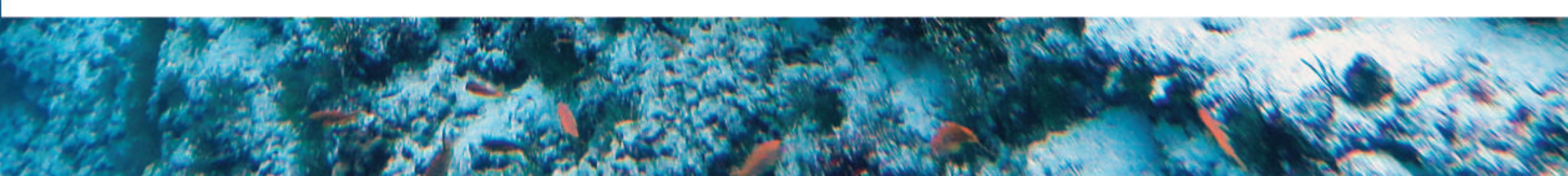

Shri Mahavir Machchhimar Sahakari Mandali Ltd.

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Deployment of Artificial Reefs: The Society has deployed around 4000 Artificial Reef Blocks in the Sea to foster breeding areas for marine fish and to conserve fish eggs and larvae. The Society organises regular meetings to expand this initiative among the fishing community.

Tackling Marine Plastic Pollution: Aligned with the Prime Minister's Vision of **Swach Bharat Samrudh Bharat** and **Swach Samudra Surakshit Samudra**, the Society promotes retrieval of plastic from the sea by the fishermen during fishing trips, for which the Society has facilitated collection facilities in the Fishing Harbours.

Fostering Education: Each year, the Society distributes around 15000 books, free of charge to schools in the District, empowering school children with valuable resources.

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Organised by

The Marine Biological Association of India, Kochi

In collaboration with

ICAR-Central Marine Fisheries Research Institute, Kochi

Bay of Bengal Programme IGO, Chennai &

National Fisheries Development Board, Hyderabad

Souvenir
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श्री शिवराज सिंह चौहान
कृषि एवं किसान कल्याण और
ग्रामीण विकास मंत्री, भारत सरकार
कृषि भवन, नई दिल्ली

सत्यमेव जयते

संदेश

संदेश

मुझे यह जानकर अत्यंत हर्ष हो रहा है कि भारतीय समुद्री जैविक संघ (एम. बी. ए. आइ.) भा. कृ. अनु. प.- केन्द्रीय समुद्री मात्स्यिकी अनुसंधान संस्थान (भा. कृ. अनु. प.- सी एम एफ आर आइ), कोच्ची के साथ मिलकर दिनांक 04 से 06 नवंबर, 2025 तक कोच्ची में समुद्री पारितंत्र – चुनौतियाँ एवं अवसर (MECOS 4) पर चौथा अंतर्राष्ट्रीय परिचर्चा का आयोजन किया जा रहा है।

भारत का समुद्री पारितंत्र जैव विविधता का अमूल्य भण्डार है और हमारे तटीय क्षेत्रों में लाखों लोगों के लिए जीविका और आजीविका का मुख्य स्रोत है। हाल के वर्षों में, जलवायु परिवर्तन, आवास क्षरण और समुद्री स्तर में वृद्धि के कारण संसाधनों की सुरक्षा और स्थायी प्रबंधन की आवश्यकता बढ़ गयी है।

मैं MECOS–4 को विशिष्ट मंच प्रदान करने के कदम की सराहना करता हूँ, जहाँ वैज्ञानिक, नीति निर्माता और हितधारक, समुद्री पारिस्थितिकी में नई चुनौतियों और समुद्री पारितंत्र के प्रबंधन के लिए नवीन रणनीतियो पर विचार आदान – प्रदान कर सकते हैं। विज्ञान आधारित नीति निर्माण को बढ़ावा देने, मात्स्यिकी और जलजीव पालन में तकनीकी नवाचार को प्रोत्साहित करने, महासागरों की दीर्घकालिक लचीलापन और स्वास्थ्य सुनिश्चित करने के लिए परिचर्चाएँ महत्वपूर्ण हैं।

कृषि एवं किसान कल्याण मंत्रालय, हमारी राष्ट्रीय प्राथामिकताओं और अंतर्राष्ट्रीय दायित्वों के अनुरूप उन्नत समुद्री अनुसंधान और टिकाऊ मात्स्यिकी शासन को आगे बढाने वाली पहलों के प्रति प्रतिबद्ध है।
मैं इस महत्वपूर्ण आयोजन की सफलता हेतु सभी प्रतिभागियों एवं आयोजकों को हार्दिक शुभकामनाएँ देता हूँ।

शिवराज सिंह चौहान

MARINE ECOSYSTEMS CHALLENGES AND OPPORTUNITIES

श्री राजीव रंजन सिंह उर्फ ललन सिंह
पंचायती राज मंत्रीग्रामीण विकास मंत्री,
और मत्स्य पालन, पशु पालन एवं डेयरी
भारत सरकार

सत्यमेव जयते

संदेश

मुझे यह जानकर प्रसन्नता हो रही है कि भारतीय समुद्री जैविक संघ (MBAI) भा. कृ. अनु. प.- केन्द्रीय समुद्री मात्स्यिकी अनुसंधान संस्थान (ICAR-CMFRI), कोच्ची के संयुक्त तत्वावधान में दिनांक 4 से 6 नवंबर, 2025 तक कोच्ची, केरल में "समुद्री पारितंत्र – चुनौतियाँ एवं अवसर (MECOS 4)" विषय पर चौथी अंतर्राष्ट्रीय परिचर्चा का आयोजन किया जा रहा है।

जैव विविधता से परिपूर्ण भारत का समुद्री पारितंत्र हमारी तटीय अर्थव्यवस्था, खाद्य सुरक्षा और सांस्कृतिक विरासत का आधार है। विस्तृत तटरेखा और जीवंत मछुआरा समुदायों के साथ हमारा देश समुद्री क्षेत्र में टिकाऊ विकास का नेतृत्व करने की अद्वितीय स्थिति में है। किंतु जलवायु परिवर्तन, प्रदूषण और संसाधनों का अतिविदोहन, विज्ञान आधारित समाधान और सशक्त सामूहिक कार्रवाई की तत्काल आवश्यकता को रेखांकित करते हैं।

MECOS–4 वैश्विक विशेषज्ञों, शोधकर्ताओं और हितधारकों के लिए समुद्री पारितंत्र के संरक्षण और टिकाऊ प्रबंधन से जुडी चुनौतियों और अवसरों पर विचार- विमर्श करने हेतु एक महत्वपूर्ण मंच प्रदान करेगा। यह परिचर्चा भारत की उस टिकाऊ नीली अर्थव्यवस्था की दृष्टि के अनुरूप है, जो नवाचार, लचीलापन और सक्रिय सामुदायिक सहभागिता पर आधारित है।

मैं समुद्री अनुसंधान को आगे बढाने और अंतर्राष्ट्रीय सहयोग को प्रोत्साहित करने के लिए MBAI तथा ICAR-CMFRI की दृढ़ प्रतिबद्धता की सराहना करना चाहता हूँ। मुझे विशवास है कि MECOS–4 की चर्चाएँ एवं उनके निष्कर्ष राष्ट्रीय तथा वैश्विक समुद्री संरक्षण प्रयासों में सार्थक योगदान देंगे।
मैं इस महत्वपूर्ण कार्यक्रम की सफलता के लिए सभी प्रतिभागियों और आयोजकों को शुभकामनाएँ देता हूँ।

श्री राजीव रंजन सिंह उर्फ ललन सिंह

Shri George Kurian
Minister of State for Fisheries,
Animal Husbandry & Dairying and
Minority Affairs, Government of India

सत्यमेव जयते

Message

Message

I am pleased to learn that the Marine Biological Association of India (MBAI), in collaboration with the ICAR-Central Marine Fisheries Research Institute is organizing the Fourth International Symposium on 'Marine Ecosystems Challenges and opportunities' (MECOS 4) from 4 to 6 November, 2025 at Kochi, Kerala

Marine ecosystems are vital for sustaining livelihoods, ensuring nutritional security and fostering economic growth. particularly for coastal communities. As India advances towards the sustainable development of its fisheries and aquaculture sectors, it is imperative that this progress be grounded in scientific excellence and driven by innovation.

MECOS 4 provides an invaluable platform for researchers, professionals and policy makers to exchange knowledge, strengthen collaboration and addressing issues such as climate change, overexploitation of marine resources and emerging opportunities in mariculture an d marine biotechnology. I am confident that the deliberations at this symposium will significantly contribute to shaping effective strategies for the long-term sustainability and resilience for our marine ecosystems.

I commend MBAI and ICAR-CMFRI for their timely initiative and I extend my best wishes for the successful of MECOS 4 with outcomes that will benefit both our marine environment and the communities that depend upon it.

George Kurian

3rd October 2025

Shri Saji Cherian
Minister for Fisheries, Culture & Youth Affairs
Government of Kerala
Thiruvananthapuram

Message

Message

I am delighted that the Marine Biological Association of India (MBAI), in collaboration with the ICAR-Central Marine Fisheries Research Institute (ICAR-CMFRI), is organizing the Fourth International Symposium on Marine Ecosystems - Challenges and Opportunities (MECOS 4) from 4 to 6 November 2025 at Kochi, Kerala.

Kerala, with its long coastline and rich marine heritage, has always emphasized the sustainable growth of its marine and fisheries sectors. At a time when challenges such as climate change, coastal erosion, and biodiversity loss are intensifying, platforms like MECOS 4 play a vital role in bringing together scientists, policymakers, and stakeholders to chart innovative and sustainable solutions.

The gathering of leading experts from across the globe at this Symposium will not only enrich scientific knowledge but also strengthen the development of sound policies to safeguard marine ecosystems and ensure the well-being of coastal communities.

I extend my sincere appreciation to MBAI and ICAR-CMFRI for hosting this prestigious event in Kerala. I wish MECOS 4 every success in advancing dialogue, collaboration, and action towards a sustainable marine future.

With Regards,

Saji Cherian

23rd September 2025

Message

Dr. M. L. Jat
Secretary Dare & Director General (ICAR)
Department of Agricultural Research & Education (DARE) &
Indian Council of Agricultural Research (ICAR)
Ministry of Agriculture and Farmers Welfare
Krishi Bhavan, Government of India New Delhi 110 00 1

Message

It gives me great pleasure to learn that the Marine Biological Association of India (MBAI), in collaboration with the ICAR-Central Marine Fisheries Research Institute (ICAR-CMFRI) is organizing the Fourth International Symposium on 'Marine Ecosystems Challenges and Opportunities' (MECOS 4) from 4 to 6 November, 2025 at Kochi, Kerala.

Marine ecosystems plays indispensable role in supporting biodiversity ensuring food security, and sustaining millions of livelihoods. However, these vital systems face mounting pressures from climate change, overexploitation, pollution and habitat degradation Against this backdrop. MECOS 4 is both timely and highly significant.

The symposium offers a dynamic platform for scientists, academicians, resource managers and policy experts from around the world to deliberate on contemporary issues and chart future directions for marine ecosystem research and conservation. The collaborative efforts of MBAI and ICAR-CMFRI in hosting this prestigious international event underscore not only India's leadership in marine science and fisheries research but also its commitment to advancing sustainable ocean governance.

I am confident that the deliberations at MECOS 4 will generate valuable insights and foster meaningful collaborations, contributing to the sustainable development and effective management of our marine resources.

I extend my best wishes to the organizers and participants for a highly successful and impactful symposium.

M. L. Jat

4th September 2025

Message

Dr. J.K. Jena
Deputy Director General (Fisheries Science)
Indian Council of Agricultural Research
Krishi Anusandhan Bhawan-II, Pusa
New Delhi-110012

Message

I am pleased to note that the Marine Biological Association of India (MBAI), in collaboration with the ICAR-Central Marine Fisheries Research Institute is organizing the Fourth International Symposium on 'Marine Ecosystems- Challenges and Opportunities' (MECOS 4) from 4 to 6 November, 2025 at Kochi, Kerala.

The marine ecosystem forms a vital component of our planet's health, playing a critical role in preserving global biodiversity, regulating the climate, and sustaining the livelihoods of millions - particularly in coastal regions. As the apex institution for agricultural research in India, ICAR remains steadfast in its commitment to advancing scientific understanding and fostering sustainable management of natural resources, with a special focus on marine and coastal ecosystems.

MECOS 4 will serve as an invaluable platform for uniting eminent scientists, young researchers, policymakers and stakeholders from across the globe to deliberate on contemporary challenges, emerging opportunities and innovative solutions in marine ecosystems science and governance. Such knowledge exchange and collaboration are vital to fortifying India's contribution towards a resilient blue economy and the achievement of the sustainable Development Goals.

I extend my best wishes to the organizers for the success of the symposium and commend their efforts in contributing signification to marine conservation, sustainable fisheries and ecosystem based management.

With Regards,

3/9/2025

J.K. Jena

3rd September 2025

Dr. Grinson George
Director, ICAR- CMFRI, Kochi &
President, MBAI, Kochi

Foreword

It is a great privilege and immense pleasure for the ICAR-Central Marine Fisheries Research Institute (CMFRI) to host the prestigious Fourth International Symposium on Marine Ecosystems Challenges and Opportunities (MECOS 4), in collaboration with the Marine Biological Association of India (MBAI).

The convening of MECOS 4 comes at a pivotal juncture, where the health of our oceans stands as a critical global concern, intrinsically linked to the well-being of humanity. Our marine ecosystems are increasingly challenged by human activities, climate change impacts, and the imperative for Blue Growth. This symposium, with its focused themes- Ecosystems and Biodiversity Conservation, Sustainable Fisheries and Mariculture, Climate and Environment Resilience, and Products, Value Chains and Livelihoods-offers a crucial platform to address these complex issues.

For more than seven decades, CMFRI has been at the forefront of marine fisheries research, dedicated to the sustainable management of India's vast marine resources and the pioneering of mariculture technologies. The discussions and deliberations at MECOS 4 are thus deeply aligned with our institutional mandate, emphasizing the need for robust scientific research to inform policy and on-ground action. We look forward to the innovative solutions and roadmaps that will emerge from the diverse expertise gathered here, spanning global scientists, researchers, policymakers, and industry stakeholders.

All the articles in the Souvenir are invited from eminent researchers who have wide exposure in research and policy making in marine fisheries, and mariculture. This Souvenir is a testament to the collective dedication and intellectual capital focused on the marine realm. It serves as a valuable record of the insights, and key information from many of the participating institutes and organizations, highlighting the significant efforts being undertaken toward achieving the Sustainable Development Goal 14 (Life below Water).

I extend my sincere appreciation to the MBAI, the organizing committee, ICAR, New Delhi, Directors and Heads of different institutes, and all participants whose active engagement will undoubtedly make MECOS 4 a grand success and a watershed moment for marine science. Let us use this occasion to forge stronger collaborations, share ground-breaking knowledge, and commit renewed efforts to ensure a Healthy Ocean for a Healthy Humanity.

With Regards,

28th October 2025

Grinson George

Sponsors

Contents

Enhancing India's Fisheries: The Role of the NFDB in Sectoral Development

Bijay Kumar Behera

Chief Executive
National Fisheries Development Board
Department of Fisheries, Government of India
Fish Building, PVNR Expressway, SVPNPA, Hyderabad- 50052, Telengana

The National Fisheries Development Board (NFDB) established in 2006, is an autonomous organization functioning under the administrative control of the Department of Fisheries (DoF), Ministry of Fisheries, Animal Husbandry and Dairying (MoFAHD), Government of India (GoI). Headquartered in Hyderabad, Telangana, NFDB operates through two regional centres: the Eastern Regional Centre (NFDB-ERC) located in Bhubaneswar, Odisha, and the North Eastern Regional Centre (NFDB-NERC) situated in Guwahati, Assam. Additionally, it manages an Integrated Coastal Aquaculture Facility at Mulapolam, Andhra Pradesh, supporting specialized aquaculture initiatives. NFDB directs its efforts toward all facets of fisheries and aquaculture, encompassing the entire value chain from production to marketing. The Board invests in the application of modern research and development tools to optimize fisheries production and productivity. It facilitates the establishment of advanced infrastructure for effective fisheries management and optimal resource utilization. NFDB also prioritizes capacity building by training and empowering stakeholders across the sector, thereby generating substantial employment opportunities. Furthermore, it strives to enhance the contribution of fisheries to food and nutritional security while promoting the sustainable management and conservation of natural aquatic resources.

Role of NFDB

A wide range of fisheries and aquaculture development activities are carried out by NFDB which can be summarised as below:

Livelihood Development and Entrepreneurship

The National Fisheries Development Board (NFDB) plays a pivotal role in enhancing the livelihoods of over 2.8 crore fisheries and aquaculture stakeholders across India. Under the Pradhan Mantri Matsya Sampada Yojana (PMMSY), NFDB implements the Group Accident Insurance Scheme (GAIS) to provide financial and livelihood security to fishers in cases of accident, disability, or hospitalization and Fishing Vessel Insurance. Additionally, under the Pradhan Mantri Matsya Kisan Sah Samridhi Yojana (PM-MKSSY), Aquaculture Insurance is offered to fish farmers to mitigate crop loss from unavoidable risks, covering one lakh hectares of aquaculture farms nationwide.

Guided by the Honourable Prime Minister's vision of "Sahakar-se-Samriddhi" (Prosperity through Cooperation), the NFDB is actively engaged in the formation and strengthening of Fisheries Cooperative Societies (FCSs), transforming them into multidimensional and multipurpose economic entities. The Board aims to establish 6,000 new FCSs and strengthen 5,500 existing ones through financial assistance under various Government of India schemes, including PMMSY, PM-MKSSY, and the Fisheries and Aquaculture Development Fund (FIDF). To support the initiation of business activities, NFDB provides a one-time grant of ₹3 lakh to each newly formed FCS. These societies are required to undergo structured training and prepare a viable business plan, based on which the financial assistance is disbursed through the respective State Fisheries Department. This initiative is designed to empower small and marginal farmers, by providing essential forward and backward linkages, skill development opportunities, and access to processing and cold chain infrastructure, which are expected to significantly enhance income generation and livelihood security.

Apart from these, NFDB implements beneficiary-centric development programmes under the framework of 'Entrepreneur Models'. As part of the PMMSY, a dedicated allocation of ₹100 crore has been earmarked for this component. The objective is to catalyse private investment and foster start-ups in fisheries and aquaculture through integrated business models that offer end-to-end solutions—spanning production, marketing, and both backward and forward linkages. A few of the key interventions established under this model include integrated Recirculating Aquaculture Systems (RAS) and Biofloc technology for shrimp farming with associated processing facilities, pre-processing units along with Individual Quick Freezing (IQF) to enhance value addition, Genetic improvement centres to strengthen breed quality etc. These initiatives collectively aim to modernize the sector, improve productivity, and create sustainable livelihood opportunities.

Infrastructure Development

To promote modern harvest and post-harvest technologies, NFDB supports the introduction of deep-sea fishing vessels and development of shore-based infrastructure such as fishing harbours, landing centres, and ice plants. It also finances cold storages, transport facilities, integrated cold chains, processing units, and modern fish markets to enhance fish handling, storage, and marketing. In aquaculture, NFDB provides financial assistance for brood banks, hatcheries, feed mills, disease diagnostic labs, quarantine facilities, cage culture systems, and modernization of fish seed farms. It also facilitates advanced fisheries training centres to foster innovation, knowledge sharing, and sustainable practices. These initiatives are supported under the FIDF, offering low-interest loans and complementing the PMMSY.

Aquaculture Promotion

NFDB encourages intensive aquaculture such as Recirculatory Aquaculture System (RAS) & Biofloc system for aquaculture, culture-based fisheries in reservoirs and wetlands, cage aquaculture to utilise vast waterbodies, shrimp culture in inland saline areas, cold-water aquaculture in raceways, diversification of aquaculture species etc.

In coordination with the DoF, GoI, NFDB identifies and supports the development of geographically concentrated areas focused on specific fisheries and aquaculture activities.

In continuation of this, the DoF, GoI has announced 34 such clusters across the country including Pearl Culture Cluster in Hazaribagh, Jharkhand, Ornamental Fisheries Cluster in Madurai, Tamil Nadu, Seaweed Cluster in Lakshadweep, Tuna Cluster in Andaman & Nicobar, Organic Fisheries Cluster in Soreng District, Sikkim etc.

Promotion of Quality Fish Seed for Sustainable Aquaculture

NFDB-ERC-National Freshwater Fish Brood Bank (NFFBB) is dedicated to enhancing fish seed quality and promoting the production of Genetically Improved Fish Species (GIFS) through a nationwide network of registered hatcheries and seed growers. Under this networking initiative, genome-improved varieties such as AhR Jayanti Rohu, Amrit Catla, Amur Common Carp, CIFA-GI Scampi, and Maha Magur are propagated and distributed to 78 network hatcheries across India to ensure quality seed supply to farmers. Additionally, the NFDB-Integrated Coastal Aquaculture Facility at Mulapolam has been developed to meet the seed requirements for Indian Pompano and Sea Bass, thereby supporting the growth of mariculture in the country.

Support for Technology and Innovation

The Board spearheads innovative research and technology demonstration initiatives, extending funding support to Fisheries Research Institutes under the Indian Council of Agricultural Research (ICAR), as well as Central and State Agricultural Universities. The research agenda encompasses a wide spectrum of emerging and transformative domains, including Precision Aquaculture, Multi-Trophic Aquaculture, Genome Improvement, Fuel-Efficient Fishing Technologies, Fish Species Diversification, Production Enhancement, Post-Harvest Quality Preservation, Abandoned, Lost or Discarded Fishing Gear (ALDFG) mitigation, Internet of Things (IoT) applications, Drone Technology, Aquaponics, and the development of Reservoir and Wetland Fisheries.

To showcase the potential of drone technology in fisheries and aquaculture, NFDB—under the aegis of the Department of Fisheries (DoF), Government of India—has launched nationwide outreach programmes featuring drone demonstrations. These initiatives aim to highlight the multifaceted utility of drones, including the transportation of fresh fish, dispensing of fish inputs, and distribution of emergency aid such as life jackets, thereby promoting technological integration and operational efficiency across the sector.

Diversification and Sustainability

NFDB promotes species and process diversification along with climate-resilient practices to address evolving environmental and market challenges. It supports seaweed, bivalve, and pearl culture; development of genetically improved fish varieties; and breeding of indigenous species, especially from Northeast India including process diversification such as cage culture, RAS, biofloc systems, IMTA etc. To advance environmental sustainability, NFDB endorses artificial reefs, fish aggregation devices, and fuel-efficient otter boards. The NFDB implemented project of development of 100 Climate-Resilient Coastal Fishing Villages (CRCFVs) with an outlay of ₹200 crore under PMMSY, focuses on modernizing infrastructure and adopting safety measures and climate-resilient practices. Another project, river ranching under PMMSY is being implemented across major river systems to replenish native fish stocks and improve fisher livelihoods. Fingerlings of Rohu, Catla, Mrigal, Brown Trout, and other indigenous species are being ranched. Similarly, sea ranching is conducted in coordination with coastal states—Gujarat, Tamil Nadu, Andhra Pradesh, and Kerala—targeting species like Cobia, Silver Pompano, and Indian Pompano.

Human Resource Development

NFDB collaborates with and provides financial support to central and state government departments, ICAR institutions, research bodies, and private agencies to implement skill development, training & capacity-building programmes and field exposure visits for fisheries and aquaculture stakeholders. It organizes conferences, workshops, and events to highlight technical innovations and foster dialogue within the fisheries sector. To promote domestic fish consumption and public outreach, NFDB organizes fish festivals across the country. The Board has also instituted Awards and Recognitions to honour best-performing fisheries entities.

Digital Initiative

NFDB is implementing the Fish Market Price Information System (FMPIS), a 'smartphone-Android-based platform that collects and analyses fish price data from major markets to support informed decision-making, from 2019. FMPIS is now integrated with National Fisheries Digital Platform (NFDP) to provide real time fish price data for informed decision making. FMPIS supports fishers, farmers, vendors, and entrepreneurs by improving market efficiency and enhancing affordability for consumers. It provides weekly price analysis reports covering fishing harbours, landing centers, wholesale, and retail fish markets across all States and Union Territories of India. The system currently tracks prices of 138 commercially important fish species.

Policy Implementation

NFDB is a key implementing agency for government schemes like the PMMSY, its sub-scheme PM-MKSSY and FIDF by facilitating project appraisal, monitoring, & capacity building and aligning national policy with grassroots execution. The developmental activities of NFDB are being implemented under different initiatives of GoI, through the State & Union Territory Governments and other End Implementing Agencies (EIA).

In essence, NFDB is the backbone of India's fisheries transformation — bridging traditional practices with modern science to ensure food security, economic growth, and environmental sustainability.

Avenues for Scientific Engagement and Collaboration

PMMSY & its sub-scheme PM-MKSSY offer a robust platform for the scientific community to scale up research outcomes and transition from basic to applied research, addressing critical gaps in the fisheries sector. Fully funded components such as genetic improvement programmes, Nucleus Breeding Centers (NBCs), innovative projects, technology demonstrations including startups and pilot initiatives, training and capacity building, aquatic quarantine facilities, and disease monitoring networks present significant opportunities for exploration and collaboration.

Participatory Approaches for a Sustainable Blue Economy: Advancing Fisher-Led Ocean Plastic Retrieval and Community-Driven Marine Governance in India

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Marine plastic pollution is one of the most serious environmental challenges of the 21st century (Prasetiawan *et al.*, 2022; Muhandiram *et. al.*, 2025). From macroplastics floating across oceans to microplastics infiltrating marine food webs, plastic waste has a cascading impact on biodiversity, fisheries productivity, and human health (Jambeck *et al.*, 2015; Rochman *et al.*, 2016; UNEP, 2021). India's vast coastline and thriving fishing industry make it particularly vulnerable to marine litter accumulation, especially near fishing harbours and landing sites.

Conventional clean-up approaches alone are insufficient to address this systemic challenge. Sustainable solutions require community participation, behavioural transformation, and governance mechanisms that integrate environmental responsibility with economic activity. Recognising this, the Marine Products Export Development Authority (MPEDA), under the Ministry of Commerce and Industry, has initiated participatory programmes through its extension arm NETFISH (Network for Fish Quality Management and Sustainable Fishing). These initiatives align with Blue Economy principles and the United Nations Sustainable Development Goals (SDGs), particularly SDG 14 (Life Below Water).

Institutional Response

MPEDA has long supported sustainable and ethical fishing practices. Building on its close ties to fishing communities, it introduced community-led ocean plastic retrieval projects aimed at empowering fishermen as stewards of the ocean. These projects incorporate plastic collection into regular fishing activities and create connections for recycling and circular economy uses.

"Suchitwa Sagaram" and DROP (Drive to Recover Ocean Plastic), two flagship initiatives, offer practical illustrations of how participatory techniques can have a beneficial simultaneous impact on the environment, community, and economy.

Suchitwa Sagaram – A Clean Sea Initiative from Kollam

Launched in 2017 at Sakthikulangara-Neendakara, the twin Fishing Harbours, at Kollam, the "Suchitwa Sagaram" (meaning "Clean Sea") project was the first organized initiative in India to retrieve marine plastic waste through fisher participation. The project was conceptualized and implemented by MPEDA–NETFISH & Boat Operators Association Kollam in partnership with the Fisheries Department of Kerala, Harbour Engineering Department (HED), Suchitwa Mission Kerala, Clean Kerala Company, SAF (Society for Assistance to Fisherwomen), local self-government bodies and local fisher cooperatives. The concept arose from extensive interaction with fishers who reported severe plastic accumulation on the sea bottom up to 50 m depth, causing damage to fishing nets, propellers, and gear, and leading to workforce wastage due to the segregation of catch and plastic wastes on-board.

During fishing operations, fishermen were urged to gather plastic and other non-biodegradable garbage that became caught in their nets and bring it to shore rather than discarding it back into the ocean. To enable secure garbage collection and segregation, a specialised collection system was installed in the harbour. Under the programme, fishers were provided with eco-friendly collection bags supplied by MPEDA-NETFISH to store plastic waste retrieved during fishing operations. Upon landing, the bags are collected, sorted, washed, dried, and then taken to the plastic shredding unit established at Neendakara Harbour. These efforts are currently being carried out by about 22 women workers who are funded by SAF/HED, with technical aid from Clean Kerala Company. By transforming garbage into a useful raw material, the processed shreds and bales are then provided for recycling and reuse, including road construction projects carried out by the Harbour Engineering Department.

As a result, the Suchitwa Sagaram project became a model project that shows how interdepartmental cooperation and fisher engagement may effectively combat ocean plastic pollution. It combined environmental preservation with socioeconomic empowerment by guaranteeing cleaner harbours and fishing areas and by giving women access to employment possibilities.

Table 1: Details of plastic waste cleaned and processed under the Suchitwa Sagaram programme at Sakthikulangara-Neendakara harbours.

Sl.No.	Item	Quantity (Kg)	Income generated (Rs)
1	Total plastic cleaned (till Sep. 2025)	2,26,035.15	-
2	Bailed plastic sold to Clean Kerala Company (till Apr. 2025)	99,178.00	10,31,771.62
3	Shredded plastic sold (till May 2025)	80,697.09	17,52,798.90

Former Minister of Fisheries of Kerala, launching the bag for collecting waste from the sea

1. Receiving waste containing bags from boats; 2. Workers carrying the bags in trolleys to the segregation area; 3. Segregation of wastes; 4. Washing the plastic wastes; 5. Cleaned and dried wastes brought to the shredding unit; 6. Loading the plastic wastes into the shredding machine; 7. Shredded plastic product; 8. Stored in sacs for further use

More than 2.26 lakh kilograms of plastic have been retrieved and channelled into productive use, creating cleaner fishing grounds and new livelihood opportunities for women. Importantly, continuous awareness programmes have helped reposition fishers as "custodians of the sea"—a powerful behavioural shift. Currently, the project is operated and expanded by the Department of Fisheries, Kerala, which has begun emulating it in other coastal regions. Over time, Suchitwa Sagaram evolved into a model of collaborative ocean stewardship and became the foundation for subsequent marine litter retrieval projects in India.

DROP–Drive to Recover Ocean Plastic at Munambam

MPEDA–NETFISH, in partnership with NGOs, harbour associations, and CSR support from the HCL Foundation, established DROP (Drive to Recover Ocean Plastic) at Munambam Fishing harbour, Ernakulam, building on the Kollam model. Innovative involvement strategies like youth campaigns, flash mobs, rallies, and digital monitoring were adopted by this effort.

The DROP (Drive to Recover Ocean Plastic) initiative was launched at Munambam Fishing Harbour, Ernakulum, through the joint efforts of MPEDA–NETFISH, Plan@Earth (NGO), the Munambam Fishing Harbour Management Society (MFHMS), the Munambam Fishing Boat Owners and Operators Coordination Committee, and the Tharakans Association, Munambam, with three-year CSR support from HCL Foundation. The project was inaugurated on 27th May 2023 by Shri. Saji Chjerian, the Hon'ble Minister for Fisheries, Kerala, who also launched the project's mobile application.

MPEDA-NETFISH initiated the programme in 2021 with the support of 10 fishing vessels. It continued on a modest scale with funding contributions from MPEDA-NETFISH, NGO Plan@Earth, the Boat Owners Association, the Tharakans Association, the Munambam Fishing Harbour Management Society, and a few schools in Ernakulum district. Impressed by the efforts being taken at the harbour by MPEDA-NETFISH, HCL Foundation, Chennai, supported the project under their CSR initiative.

The NGO and MPEDA-NETFISH arranged a number of awareness-raising events prior to its introduction, such as flash mobs, student campaigns, and harbour rallies, to urge fishermen to return waste that has been recovered from the ocean and to increase public awareness of marine plastic pollution. Flash mobs, street plays, and awareness campaigns have been organised by students from Federal Institute of Science and Technology (FISAT) Angamaly, Rural Academy of Management Studies, Cherai, Choice Public School, and Global Public School Ernakulum as part of the project to involve stakeholders and raise awareness of environmental issues. With the active participation of 651 fishing vessels, the project has produced impressive results. The entire amount of plastic waste recovered as of September 2025 was 49,028 kg, of which 29,101 kg came from the sea and 19,927 kg from the portpremises. Recently, Chinese dip-net operators at Munambam have also begun contributing recovered plastic under the DROP project. The collected waste is cleaned, shredded, and recycled by Plan@ Earth, further advancing circular economy practices and sustainable resource management.

To motivate and sustain participation, incentives, awards, and mementoes are presented to fishers and associations that make significant contributions to the initiative. Awareness wall paintings depicting the impacts of plastic waste were created on the compound walls of the harbour to educate and engage the public. The project has also improved harbour cleanliness and worker welfare by introducing open-air gym facilities and indoor recreational spaces at the Munambam Fishing Harbour. By transforming Munambam into a model harbour for marine plastic recovery, the DROP initiative exemplifies MPEDA–NETFISH's success in integrating fisher participation, youth engagement, and CSR partnerships for sustainable harbour management.

Shri. Saji Cherian, the Fisheries Minister of Kerala, inaugurates the DROP project

Within just two years, the project has successfully mobilised hundreds of fishers, enhanced harbour hygiene, and integrated recovered waste into circular economy streams. The visible environmental and social impact of DROP in improving harbour sanitation and marine ecosystem health has attracted interest from other coastal states seeking to replicate this successful model. DROP is an example of a multi-stakeholder governance model that combines the commercial sector, NGOs, government, and community to promote sustainable marine management.

Plastic waste collection system at Munambam harbour, under the DROP project

Chairman, MPEDA, visits Munambam Harbour and reviews the activities under the DROP project.

Impact and Achievements

Together, Suchitwa Sagaram and DROP have recovered more than 2.75 lakh kilograms of plastic waste from Kerala's coastal waters. Beyond clean-up, the initiatives demonstrate:

- Environmental gains: Cleaner fishing grounds, reduced litter load, improved ecosystem health.
- Economic value creation: Plastic converted into raw material for recycling and road construction, creating local employment.
- Social empowerment: Engagement of women workers in plastic processing, and transformation of fishers' roles from users to stewards.

These results align with India's pledges under SDGs 14 (Life Below Water), 17 (Partnerships for the Goals), and 12 (Responsible Consumption and Production). The circular economy, a production and consumption model that prioritises sharing, reusing, repairing, refurbishing, and recycling existing materials and products for as long as feasible, served as the foundation for these projects (Vassallo *et al.*, 2023). Fishermen's recovery of plastic debris from the ocean has successfully redirected it into practical applications, adding value.

MPEDA's Nationwide Effort for Plastic Waste Collection through Fishers

Inspired by the success in Kerala, MPEDA–NETFISH has mainstreamed marine litter awareness and retrieval practices across major fishing harbours and landing centres in all maritime states. Through fisher training and harbour-level programmes, fishers are now routinely bringing back entangled plastic, segregating waste, and collaborating with local agencies for disposal and recycling. This institutionalisation of participatory practices marks a significant step towards embedding environmental responsibility in the fisheries sector nationwide.

Through fisher training and harbour-level meetings, MPEDA-NETFISH has effectively motivated fishers to:

- Bring back plastic waste that gets entangled in their nets or is found floating during fishing operations.
- Segregate and store the collected waste in designated locations at harbours and landing centres.
- Collaborate with local self-government bodies, harbour committees, and NGOs for safe disposal or recycling.

This integrated model not only keeps fishing grounds cleaner but also prevents waste from returning to the ocean. Through persistent awareness creation, MPEDA-NETFISH has instilled a culture of "Bring Back, Not Throw Back" among fishers, transforming waste retrieval into a regular, community-driven practice rather than an occasional effort.

Key outcomes include:

- Significant reduction in marine litter near principal fishing harbours.
- Improved harbour hygiene and sanitation.
- Increased awareness among fishers on waste segregation and recycling.
- Establishment of linkages with recycling agencies and local bodies for circular waste management.
- Replication potential as a national model for fisher-driven marine plastic retrieval.

Alignment with Blue Economy, UN SDGs & National policy on Marine Fisheries

These initiatives directly contribute to India's Blue Economy Vision, the United Nations Sustainable Development Goals (SDGs) and National Policy on Marine Fisheries:

- SDG 14 (Life Below Water): Reducing marine plastic and protecting ecosystems.
- SDG 12 (Responsible Consumption and Production): Promoting recycling and the circular economy.
- SDG 17 (Partnerships for the Goals): Building collaborative networks among government, fishers, and civil society.

MPEDA's initiatives for safe collection and disposal are aligned with the National Policy on Marine Fisheries, 2017, which emphasises strengthening regulatory mechanisms to control pollutants and ensure effective management of both land-based and sea-based sources of pollution (NPMS, 2017)

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Way Forward

MPEDA aims to expand its plastic retrieval model to all principal fishing harbours of India through MPEDA-NETFISH, in collaboration with State Fisheries Departments, local authorities and NGOs. Future actions include:

- Establishing 'Clean Harbour Zones' with integrated waste collection, segregation, and recycling systems.
- Incentive-based schemes for fishers practising regular plastic retrieval.
- Development of digital monitoring systems to record marine litter data through the Harbour Data Collection framework.
- Research collaborations on upcycling marine plastic into usable products.

A Sustainable Solution for a Global Problem

Plastic marine litter is recognised as one of the most widespread and persistent environmental challenges globally (UNEP, 2021). They have lethal impacts on a wide range of marine life, including whales, seals, turtles, birds, fish, as well as marine invertebrates such as bivalves, plankton, and corals (Rochman *et al.*, 2016). Plastic pollution in the marine ecosystem is well documented; however, the exact quantity of plastic entering the oceans from different sources, particularly through riverine runoff, has not yet been accurately quantified (Jambeck *et al.*, 2015). However, recognising the alarming increase in marine litter and plastic pollution, serious efforts have been undertaken in various parts of the world to quantify the extent of the problem (Eriksen *et al.*, 2014; Cózar, A., *et al.*, 2014). Similarly, studies have also been conducted to examine the impact of plastic pollution in the marine ecosystem (Rochman *et al.*, 2016; Campa *et al.*, 2019; UNEP, 2021). Globally, ocean plastic retrieval programmes are being implemented to address the growing plastic pollution crisis, with prominent initiatives such as "The Ocean Cleanup" focusing on developing innovative systems for cleaning up both oceans and rivers (Giezen and Wiegmans, 2020). At present, the Government of India has launched several initiatives to combat marine plastic pollution, including the Swachh Sagar, Surakshit Sagar (Clean Coast, Safe Sea) campaign, the India–Norway Marine Pollution Initiative, and the GloLitter Partnerships Project, all aimed at reducing sea-based plastic litter and promoting sustainable ocean management. These efforts are supported by national policies like the ban on single-use plastics, the Plastic Waste Management Rules, and international partnerships.

MPEDA, through its society MPEDA–NETFISH, has implemented effective plastic collection and safe recycling programmes across selected coastal states of India, engaging the fisher community and ensuring the active participation of NGOs and other partner agencies. It is therefore timely to replicate such initiatives across all coastal regions, with funding support from the Government and other agencies to establish sustainable plastic recovery and recycling projects.

Conclusion

Marine plastic retrieval from isolated clean-up drives can be transformed into sustainable governance mechanisms through the use of participatory methods, as demonstrated by the Suchitwa Sagaram and DROP initiatives. By incorporating community involvement into national strategies, India can empower fishermen as ocean stewards and further its Blue Economy ambition.

Finding more than 2.75 lakh kilogrammes of ocean garbage is not just a significant environmental achievement; it is also a behavioural change. India can become a global leader in participatory marine plastic reduction by scaling up these models across the country, which would have a long-lasting effect on the environment, economy, and society.

Status, Issues and Strategies for Mariculture Development in India

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Mariculture—the cultivation of marine organisms—offers India a transformative opportunity to expand seafood production, strengthen its blue economy, and uplift coastal livelihoods. With an extensive coastline stretching over 11,099 kilometers and a vast Exclusive Economic Zone (EEZ) of 2.2 million km^2 area, a continental shelf area spanning for 0.5 million km^2, 1.2 million hectare of coastal salt affected land and 3.9 million hectare of estuarine area; the country holds tremendous potential to emerge as a global mariculture leader. Despite pioneering research and recent government efforts, the sector remains underdeveloped, with current output falling far short of its estimated annual capacity of 4 to 8 million tonnes.

Status

Potential: Scientific evaluations have been undertaken to pinpoint optimal locations for various mariculture activities. ICAR-CMFRI has geo-referenced hundreds of such sites, laying the groundwork for a structured expansion of the sector.Among these, 146 cage farming sites have been identified, covering over 47,000 hectares and offering an estimated annual yield of 2.13 million tonnes. Additionally, ICAR-CMFRI has mapped more than 24,000 hectares suitable for seaweed cultivation along the coast. The Andaman and Nicobar Islands, along with Lakshadweep, present vast yet underutilized opportunities. Their extensive EEZs and pristine deep waters make them ideal for tuna clusters and open-ocean mariculture. Recognizing this potential, the government has launched targeted initiatives to tap into the marine wealth of these island territories.

Expanding Horizons: Diversification in Mariculture

Traditionally reliant on shrimp monoculture, India's mariculture sector is now embracing diversification by venturing into high-value marine finfish, molluscs, and seaweeds. ICAR-CMFRI has pioneered captive breeding and seed production technologies for over 13 commercially significant food finfish species. Prominent candidates for cage culture include cobia, silver pompano, Indian pompano, seabass, groupers, giant trevally, and snappers. To support commercial scalability, specialized infrastructure such as the National Brood-bank Facility ensures consistent availability of high-quality seeds. India has also successfully commercialized the cultivation of green mussels and edible oysters, particularly along the coasts of Kerala, Karnataka, and Goa. While the country possesses a strong resource base for pearl oyster farming, its expansion is constrained by the high capital requirements for hatchery and processing infrastructure. Other molluscs like clams and cockles also present viable farming opportunities. On the ornamental front, global demand for marine aquarium species is rising, positioning India as a potential key exporter. ICAR-CMFRI has developed seed production technologies for more than 27 high-value ornamental fish species. Introducing green certification for these varieties could help establish a sustainable and lucrative export market.

Species

Under its mandate, ICAR-CMFRI has prioritized 76 marine species including food fishes and ornamental fishes, molluscs, crustaceans, and ecologically significant invertebrates for

seed production and farming technology development. Notably, year-round seed production technologies have been successfully developed for thirteen high-value marine food fishes, most important of which are cobia, silver pompano, Indian pompano, orange spotted grouper, pink ear sea bream, and John's snapper. Similarly, seed production technology has been perfected for 27 premium ornamental species, including five crossbred varieties.ICAR–CMFRI has established National Brood-bank Facilities for cobia and silver pompano, two high-potential species for sea cage farming. Located at Mandapam and Vizhinjam, these centers produce 48 million silver pompano larvae and 30 million cobia larvae annually, ensuring a reliable supply of high-quality seed and reducing dependence on wild broodstock. Also, to scale up operations, ICAR-CMFRI has signed MoUs with seven private and state-run hatcheries for technology transfer.

Farming Systems

Sea cage farming has emerged as a scalable and economically viable model for intensive finfish production in India's coastal waters, with significant innovations in cage design and mooring systems since its inception in 2007. Participatory demonstration projects involving fishermen cooperatives and coastal entrepreneurs have fostered community ownership and operational capacity. ICAR–CMFRI has standardized Good Sea Cage Farming Practices and developed two indigenous cage models—6-meter diameter cages made from Galvanized Iron (GI) and High-Density Polyethylene (HDPE)—yielding 1.5-2 tonnes of fish per cycle and economic returns of ₹1.0–1.5 lakh per 8-month crop per cage. Institutional support through the Blue Revolution Scheme and PMMSY has further propelled adoption across states like Maharashtra, Tamil Nadu, Kerala, Karnataka, and Odisha, reinforcing sea cage farming as a key pillar of India's mariculture strategy.

Seaweed farming is rapidly emerging as a low-cost, eco-friendly livelihood option with immense potential for coastal communities in India, offering high returns with minimal inputs. Proven models like the floating raft system adopted by SHGs in Tamil Nadu's Palk Bay region demonstrate its economic viability and social inclusiveness, especially for women. A floating system of 3.7×3.7 m rafts with a 45-day farming cycle for a total of 270 production days per year is being practiced. With ICAR–CMFRI estimating a production potential of 9.7 million tonnes annually, the scope for expansion is significant. However, current production falls short of industrial demand across sectors like pharmaceuticals, cosmetics, and biofertilizers. To bridge this gap, India must invest in micropropagation, processing infrastructure, market development, and carbon credit mechanisms. Seaweed farming thus stands as both a livelihood enhancer and a strategic pillar of India's Blue Economy, fostering climate resilience and coastal empowerment.

Bivalve farming, particularly mussel and oyster culture, has expanded across the backwaters of Kerala, Karnataka, Goa, and Maharashtra due to its high profitability and low input costs, with over 2,000 farmers in North Kerala's Padanna estuary contributing nearly 75% of India's green mussel production. A number of methods such as stake culture, on-bottom culture, long-line culture, raft culture, and rack culture, are followed for mussel and oyster farming.The annual production is over 10,000 tonnes, with a production cost of Rs 90/kg versus a farm-gate price of Rs 200/kg for green mussel and Rs 5/ oyster versus a farm-gate price of Rs 15/oyster. ICAR–CMFRI has enabled commercial farming of green mussels and edible oysters, benefiting around 6,000 women-led SHGs and yielding strong profit margins. However, challenges such as inadequate marketing infrastructure, limited cold chain facilities, and lack of EU export compliance hinder growth. In pearl culture, ICAR-CMFRI's hatchery technologies for spherical and Mabe pearls face commercialization hurdles due to high investment and long gestation periods. Strategic solutions like selective breeding and triploid oyster production could unlock new value chains, provided they receive targeted policy and financial support.

Advanced Techniques

A major innovation in Integrated Multi-Trophic Aquaculture (IMTA) has emerged through the installation of 16 seaweed rafts (12 ft × 12 ft) around a 6-meter sea cage, resulting in a 122% increase in seaweed yield per 45-day cycle—adding 176 kg per raft. This ecologically sound configuration not only enhances nutrient recycling and reduces the environmental footprint of sea cage farming but also delivers significant income gains for coastal farmers. Supported by ICAR–CMFRI, the model has already been adopted by over 150 farmers in Tamil Nadu's Palk Bay region, demonstrating its scalability and community impact. By integrating seaweed cultivation with marine finfish farming, this IMTA breakthrough aligns with India's Blue Economy vision, promoting sustainable livelihoods and resilient coastal ecosystems.

Recirculating Aquaculture Systems (RAS) are advanced land-based setups that enable high-density fish farming under controlled conditions through a closed-loop water treatment process, ensuring optimal quality and biosecurity. These systems support seed production, grow-out operations, and the cultivation of exotic species like Atlantic salmon, along with year-round broodstock maturation and nursery rearing. ICAR–CMFRI has successfully developed cost-effective RAS technologies for seven marine finfish species, now adopted across coastal states. Offering minimal environmental impact, biosecure environments, space efficiency, and climate resilience, RAS stands as a cornerstone in India's strategy to modernize mariculture and boost sustainable seafood production.

These innovations have enabled sustainable mariculture expansion, species diversification, and enhanced export competitiveness for India.

Key Issues

Infrastructure Deficiencies: India's mariculture sector faces critical infrastructure gaps that hinder its growth and efficiency. The lack of adequate cold storage units, modern processing facilities, and a robust value chain results in substantial post-harvest losses. These limitations not only reduce profitability for producers but also restrict access to broader domestic and international markets.

Limited Investment: The mariculture sector in India faces significant financial barriers, especially when it comes to adopting advanced technologies. High upfront costs for systems like offshore cage farming and Recirculating Aquaculture Systems (RAS) deter widespread commercialization and hinder the scaling of operations. This investment gap restricts innovation, slows sectoral growth, and limits participation from small-scale and emerging entrepreneurs.

Regulatory and Policy Gaps: India's mariculture sector is hindered by ambiguous regulations and fragmented governance. The absence of clear, standardized guidelines for leasing marine areas creates uncertainty for stakeholders, while inconsistent state-level policies lead to overlapping jurisdictions and multi-user conflicts. These regulatory complexities pose significant hurdles for investors, slowing down project approvals and deterring long-term commitments to the sector.

Environmental Risks: India's mariculture sector is increasingly vulnerable to a range of environmental threats. Coastal water pollution driven by industrial discharge, agricultural runoff, and urban waste can degrade water quality and harm cultured species. Disease outbreaks, often exacerbated by poor biosecurity and overcrowding, pose serious risks to farm productivity. Additionally, climate change impacts such as rising sea temperatures and ocean acidification threaten ecosystem stability, species health, and long-term viability of mariculture operations.

Feed and Seed Limitations:The mariculture sector continues to rely heavily on wild-caught seed for several species, leading to inconsistent supply and potential ecological strain. Existing hatchery infrastructure struggles to meet the growing demand, creating bottlenecks in scaling up production. The economic sustainability of finfish farming is undermined by the high cost of feed, particularly those based on fish meal. In addition to financial strain, there are growing concerns about the environmental impact and long-term viability of fish meal based diets, prompting the need for alternative, eco-friendly feed solutions.

Social and Community Issues: The allocation of coastal zones for mariculture often overlaps with traditional fishing grounds, leading to tensions between mariculture operators and artisanal fishing communities. These conflicts over resource access can hinder project implementation and disrupt local livelihoods if not addressed through inclusive planning and dialogue. Small-scale mariculture practitioners frequently face barriers such as limited access to institutional credit, modern farming technologies, and timely market intelligence. These constraints make them particularly susceptible to economic shocks and reduce their ability to scale operations or compete in larger markets.

Strategies for Development

Establish Dedicated Mariculture Parks

A key approach to advancing India's mariculture sector is the creation of dedicated mariculture parks which are strategically designated marine zones exclusively reserved for aquaculture activities. These parks would be scientifically planned and sustainably managed to:

- Optimize spatial use by clearly demarcating zones for mariculture, reducing conflicts with other coastal users
- Strengthen infrastructure through integrated facilities for hatcheries, feed production, cold storage, and processing
- Empower communities by actively involving local fishers, cooperatives, and self-help groups in governance and operations
- Encourage investment via streamlined leasing procedures and targeted financial incentives
- Facilitate knowledge transfer through training centers and demonstration units in collaboration with research institutions like ICAR-CMFRI

Strengthen Institutional Support

A critical step toward advancing mariculture in India is the effective implementation of the National Mariculture Policy. This policy aims to establish a clear, consistent, and transparent regulatory framework for the leasing and licensing of marine areas. By harmonizing procedures across states and streamlining approvals, it can reduce bureaucratic delays, encourage private investment, and ensure equitable access to marine resources, thus laying the foundation for sustainable and scalable mariculture development.

Promote Species Diversification

To build a resilient and sustainable mariculture sector, it is essential to encourage species diversification. Expanding the culture of seaweeds, mussels, and high-value finfish can reduce dependence on a narrow range of species, particularly shrimp; and help mitigate biological, economic, and environmental risks. Diversification also opens new market opportunities, supports ecological balance, and enhances the adaptability of coastal farming systems to changing conditions

Invest in Post-Harvest Infrastructure

Strengthening post-harvest infrastructure is vital for unlocking the full potential of India's mariculture sector. Priority should be given to the development and modernization of cold chain systems, transportation networks, and seafood processing facilities. These improvements will reduce post-harvest losses, enhance product quality, and expand market access, both domestically and internationally. Government schemes such as the Pradhan Mantri Matsya Sampada Yojana (PMMSY) offer critical financial support to drive these infrastructure upgrades and promote sector-wide efficiency.

Prioritize Research and Development (R&D)

Strengthening R&D is essential for driving innovation and long-term sustainability in mariculture. Key focus areas include:

- Breeding and Seed Supply: Expanding the network of hatcheries and establishing nucleus breeding centers will help ensure a reliable supply of genetically improved, disease-resistant seed stock. This will enhance farm productivity and reduce dependence on wild-caught seed.
- Sustainable Feed Solutions: To address high feed costs

and environmental concerns, research should prioritize the development of alternative protein sources such as insect meal and plant-based formulations to gradually replace fish meal. These innovations can improve cost-efficiency and reduce the ecological footprint of mariculture operations.

Promote Sustainable and Innovative Practices

Scaling up the adoption of Integrated Multi-Trophic Aquaculture (IMTA) can significantly enhance environmental sustainability in mariculture. By cultivating complementary species such as finfish, shellfish, and seaweeds in a shared system, IMTA improves nutrient recycling, reduces waste discharge, and mimics natural ecosystem dynamics.

To safeguard mariculture against climate-related risks, targeted research and innovation are essential. This includes developing climate-resilient farming techniques, such as species selection based on thermal tolerance, adaptive cage designs, and early warning systems for disease and extreme weather events. These efforts will help build long-term resilience and ensure the sector's viability in a changing climate.

Empower Coastal Communities

Improving access to affordable credit is essential for empowering small-scale fishers and mariculture practitioners. Expanding the reach of financial instruments such as the Kisan Credit Card (KCC) to include marine fishers can provide timely working capital for inputs, equipment, and operational needs. Tailored financial products, simplified application processes, and awareness campaigns can further enhance credit uptake and reduce dependence on informal lending sources.

Strengthen Capacity Building

Enhancing human capital is vital for the sustainable growth of mariculture. This involves expanding training and extension services focused on:

- Scientific farming techniques, including site selection, species-specific protocols, and environmentally responsible practices
- Disease management, covering early detection, biosecurity measures, and response strategies to minimize losses and protect farm productivity

By equipping farmers, cooperatives, and local institutions with practical knowledge and skills, capacity building initiatives can improve operational efficiency, reduce risks, and foster innovation across coastal communities.

Foster Community Involvement

Ensuring meaningful participation of coastal communities is essential for the equitable and sustainable growth of mariculture. Actively involving local stakeholders in spatial planning and resource management helps:

- Address socio-economic concerns related to access, livelihoods, and cultural practices
- Minimize user conflicts by integrating traditional knowledge into zoning and site selection
- Build trust and transparency in decision-making processes
- Foster a sense of ownership and stewardship, encouraging long-term commitment to sustainable practices

Community-led governance models and inclusive consultation frameworks can transform mariculture into a socially resilient and locally supported sector.

Indian Mariculture through the 'One Health' lens: An Integrated Strategy for a Sustainable Blue Growth

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The increasing global population and rising climate change have made an extreme burden on the requirement for safe and nutritious food sources. FAO (2017) predicts that the global population will reach to 9.7 billion by 2050 and 10.2 billion by 2100, demanding ~70% increase in food production compared to 2009, to satisfy the human needs. As the terrestrial agricultural productivity has reached its limits due to the limitations caused by the increasing demands for arable land and freshwater, the focus is mainly on aquatic resources for achieving future food security. The Blue Transformation Roadmap (FAO, 2022) also emphasizes the significance of aquatic food systems in achieving nutritional and livelihood security and economic resilience. Aquaculture is the most rapidly advancing food production sector worldwide in the current scenario, with an average 4.4% growth since 2020 (SOFIA, 2024). Within aquaculture domain, mariculture, that includes the cultivation of finfish, crustaceans, molluscs, and seaweeds in marine and coastal environments, is a fast growing and energetic sector having an immense potential for development. The broader agenda of the blue economy has emphasized the significance of mariculture for sustainable utilisation of marine resources. However, it is essential to follow responsible mariculture practices to ensure the marine ecosystem health. Emerging and existing diseases, antimicrobial resistance (AMR), cumulative marine pollution, and fluctuating climatic settings threaten the sustainability of the mariculture sector. The One Health approach, which identifies the intimate relations between human, animal, and environmental health sectors, offers tactics for addressing these challenges.

An Outline of Indian Mariculture

The backgrounds of Indian mariculture date back to the 1970s, when the ICAR-Central Marine Fisheries Research Institute (CMFRI) introduced pioneering works at Mandapam and Tuticorin with the farming of seaweeds and bivalves. These early works were extended to comprise induced breeding and maturation of the Indian white shrimp and upgrading of semi-intensive shrimp cultivation systems. The mariculture activities were then extended to the cultivation of several finfishes, including cobia, silver pompano, Indian pompano, groupers, snappers, breams, sea bass, and several ornamental fishes. Furthermore, shellfish including mussels, oysters, clams, green tiger shrimp, and blue swimmer crab were added to this extension policy. Technologies for marine pearl production and seaweed cultivation are also in progress, making more paths for sustainable mariculture growth (Suresh *et al.*, 2023).

India has a vast potential for mariculture with its 11,098.81 km coastline and an Exclusive Economic Zone of >2.3 million km². In spite of a theoretic production possibility of 4 to 8 million tonnes per year, present yields remain at ~ 0.1 million tonnes (Gopalakrishnan *et al.*, 2023), stressing the extensive prospects for improving the blue economy. Insights achieved through the inland and brackishwater aquaculture activities can be applied to improve mariculture production in a strategic step-wise manner. It is crucial to launch a comprehensive national mariculture mission focusing on species prioritisation, advancement of healthy hatchery and grow-out technologies, identification of appropriate mariculture sites, and advancement of enabling policy frameworks to fully achieve this potential. Simultaneously, integrating mariculture activities within a One Health framework is crucial to ensure animal welfare, human health, and environmental protection. Applying this holistic approach can unlock the full potential of Indian mariculture, positioning the country as a global leader in the industry.

'One health' Concept in Mariculture

The 'One Health' is a collective, multisectoral, and transdisciplinary strategy to accomplish the best possible health outcomes for humans, animals, and the environment. This is based on the principle that the well-being of people, animals, and their common environment are inherently interconnected and cannot be separated from each other. Instead of focusing only on a simple target of disease prevention or management, the 'One Health' aims at maintaining optimal environmental (water, air, and sediment) qualities, climate stability, safe and maximum food production, and biodiversity protection. This approach also supports in anticipating and mitigating the emerging health issues related to intensive mariculture activities, marine pollution, and climate change, while helping resilience in environments and livelihoods. Coordinated efforts involving governments, farmers, researchers, and local communities are critical to execute this approach (Stentiford et al., 2020).

Interconnections Between Mariculture and 'One Health' components

Human health

Mariculture has a significant role in human health, food security and livelihoods by providing high-quality protein and essential fatty acids, and supporting income generation and employment. Guaranteeing seafood as nutritious and safe with minimal microbial and chemical contaminants is crucial to completely appreciate these benefits.

Virulent *Vibrio* species (especially V*. parahaemolyticus* and *V. vulnificus*) are a major health risk at the human-mariculture crossing point. Humans are exposed to these pathogens by consuming raw or undercooked seafood or by direct contact with polluted seawater via open wounds. *V. parahaemolyticus* causes gastroenteritis, while *V. vulnificus* causes severe wound infections leading to fatal septicemia, particularly in immunocompromised persons. Occupational exposure to *V. vulnificus* is a well-documented threat for mariculture workers especially in warm, brackish waters where the bacterium is ubiquitous. Climate change further worsens these hazards. Increasing sea surface temperatures, fluctuations in salinity, and nutrient enrichment due to marine pollution make advantageous circumstances for vibrio proliferation in coastal and mariculture environments. High stocking densities and stressed animals increase the vulnerability of farmed species to vibriosis, causing severe economic losses and increasing the chance of zoonotic transmission.

Though several aquatic diseases have no direct zoonotic potentials, mariculture can have many indirect impacts on human health. For instance, application of chemical therapeutics, antifouling agents, and prophylactic antimicrobials can lead to residual contamination, environmental degradation, and emergence of resistant bacterial communities. The development and transfer of AMR is one of the serious indirect impacts related to mariculture. The overuse and irresponsible use of antibiotics in intensive mariculture systems can select multidrug-resistant bacteria. These bacteria and their resistance genes can then transfer horizontally to human pathogens through the aquatic environment or seafood products, making a challenge to human and environmental health. Furthermore, antimicrobial residues in seafood can further disturb human gut and environmental microbes and promote the selection of resistant bacteria, finally reducing the efficacy of clinically important antibiotics. These threats emphasize the necessity for judicious antimicrobial use, consistent monitoring of antimicrobial residues, and the adoption of biosecurity and vaccination-based disease control policies.

Apart from AMR, poor waste and sewage management can cause raised nitrogen and phosphorus levels in water, promote harmful algal blooms, leading to toxin accumulation in seafood. Furthermore, systematic monitoring of possible contaminants including heavy metals, microplastics, biotoxins, and residual chemicals is essential for protecting consumers and guiding effective public health strategies.

Animal health

Animal health is the foundation of sustainable mariculture and a crucial element of the 'One Health' strategy. Healthy marine animals are central to ensuring food safety, ecological solidity, and financial viability. Thus, disease outbreaks among cultured animals are one of the most important challenges in mariculture, causing extensive economic losses and threatening seafood safety. Intensive farming practices, involving high stocking densities, changing water quality, suboptimal environmental settings and poor nutrition, compromise the immune systems of cultured animals, making them more vulnerable to bacterial, viral, parasitic, and fungal diseases. Apart from this, diseases from mariculture farms can spread to wild fish populations, mainly when farmed fish escape during operational or equipment failures. Escaped fish may act as vectors of pathogens, transmitting diseases to wild populations. One such disease recognised by the World Organisation for Animal Health (WOAH) is Red Sea Bream Iridoviral Disease. These risks from mariculture activities to wild populations necessitate international monitoring and coordinated response systems through the One Health lens. Besides, interbreeding between escaped and wild fish can modify genetic structures, decrease local adaptation, and reduce genetic variability, eventually threatening the biodiversity and resilience of natural ecosystems.

Beyond diseases, pollutants in the ecosystem can disturb wild and farmed marine animals, influencing animal health and product safety. The type and level of contaminants varies based on species, geographic location, feed, and farming practices. In farmed seafood, the major pollutants of concern comprise methylmercury, persistent organic pollutants, hydrocarbons, microplastics, and production-related chemical treatments. Farmed fish often acquire these pollutants from fish meal and oil derived from small pelagic trash fish. Further, the pollutants originate from industrial runoffs, hospital discharges, combustion of fossil fuels and agricultural runoff. Some international fish meal producers use activated carbon filtration to remove pollutants from fish meal and oil to reduce pollutant levels in seafood. Decreasing dependence on fish-based feed ingredients is an additional effective approach to reduce pollutant accumulation.

In brief, the health of maricultured animals is thoroughly interwoven with ecological sustainability and human health, making it a central pillar of the 'One Health' framework. Efficient aquatic animal health management relies on disease prevention, environment monitoring, and responsible cultivation practices. For example, white spot syndrome virus (WSSV) in Madagascar's shrimp farms was effectively controlled by harmonized ecological surveillance, pathogen screening of wild animals, and bio secured hatchery management (Responsible Aquaculture Foundation, 2013). Poor animal health can cause financial losses, food insecurity, and zoonotic risks, while anthropogenic influences such as pollution, antimicrobial misuse, and habitat degradation deteriorate environmental resilience and encourage disease outbreaks. Endorsing aquatic animal health within a One Health strategy thus cares sustainable seafood production, safeguards food safety, and improves the livelihoods of coastal communities.

Environmental health

Environmental health is the third keystone of the 'One Health' strategy and healthy marine ecosystems are indispensable for ensuring aquatic animal and human health. Poor water quality, pollution, and climate variations like rising temperatures or altered salinity can increase disease susceptibility and lessen productivity of farmed animals. Marine plastics can also act as vectors for pathogens, facilitating the spread of infectious diseases and AMR in marine ecosystems.

On the other hand, mariculture activities can influence environmental health. Mismanagement of feed and other wastes from mariculture farms causes extra nitrogen and phosphorus release into nearby waters, leading to algal blooms and dead zones that deplete oxygen and disturb close ecosystems. Harmful algal blooms can reduce the sunlight penetration, potentially troubling photosynthetic processes. Intensive mariculture frequently uses antibiotics, disinfectants, and other chemicals to attain maximum production, that get accumulated in sediments, affecting wild fauna, and promote antimicrobial resistance. Habitat changes, like removal of mangroves or building enclosures as part of mariculture activities, can diminish biodiversity and damage ecosystem services. In brief, intensive mariculture activities, if not managed within a One Health framework, can lead to environmental degradation, transmission of zoonotic pathogens, and spread of AMR between marine animals and humans. Encouraging sustainable ecosystem management strategies within a One Health plan is thus essential to lessen the reciprocal hazards.

Tactics for Implementing 'One Health' in Mariculture

Key tactics for implementing one health plan in mariculture include:

Sustainable farm and environmental management

- Sustainable farm management by minimizing eutrophication, pollution, and the spread of invasive species.
- Maintenance of water quality through proper site

selection, effluent treatment, and polyculture or integrated multitrophic aquaculture (IMTA), which recycles nutrients and reduces environmental impacts.

- Preservation of mangroves, seagrass beds, and coral reefs as natural buffers supporting nutrient cycling and disease regulation.
- Use of environment-friendly antifouling coatings, biodegradable cleaning agents, and enforce strict regulations on plastics and metals in mariculture activities to limit chemical pollution.
- Promotion of low-energy footprint production systems and reduce carbon costs, considering energy costs associated with production, feed inputs, operational engineering, and transport in mariculture activities.
- Promotion of low-spatial footprint mariculture systems by planning aquaculture systems in places that will conserve biodiversity and natural resource production, while protecting areas of cultural and heritage importance, or natural beauty.

Disease surveillance and biosecurity

- Integrated disease surveillance and biosecurity to prevent and manage outbreaks across farmed and wild populations.
- Use of quality cages and nets to prevent escape of farmed animals and avoid pathogen and genetic spillover.
- Monitoring of water quality and environment to maintain ecological balance and reduce stressors on aquatic organisms.
- Environmental monitoring (temperature, salinity, nutrient load, chlorophyll content, microbial indicators) and early warning systems using remote sensing, water-quality sensors, and satellite-based risk mapping to predict outbreaks.
- Implementation of risk assessment tools (chemical, animal, and human pathogen hazards) to guide practical mitigation strategies.
- Integration of metagenomics, metabolomics, and transcriptomics to link microbial dynamics with health to develop early disease/ health biomarkers.
- Adherence to strict quarantine protocols at farm, catchment and national levels to control cross-boundary risks of disease transfer.

Antimicrobial stewardship and health management

- Avoidance of prophylactic antibiotic use, minimising therapeutic antibiotic use, implementing phage therapy, and probiotics for therapeutic interventions.
- Establishment of special surveillance systems to monitor antibiotic use in mariculture to ensure that treatments follow recommended dosages, are applied only when necessary, and are administered under the supervision of qualified aquatic animal health practitioners.
- Implementation of country-specific strategies for AMR surveillance and stewardship through multisectoral collaboration, leadership development, and alignment with One Health policies.
- Regular animal health monitoring and the use of vaccination, probiotics and immunostimulants as preventive health strategies, to reduce disease incidence, morbidity, and mortality, ensuring safer seafood for consumers.

Sustainable nutrition and feed strategies

- Development of sustainable feed sources that do not compromise wild fisheries or ecosystem health.
- Nutrition and feed optimization to enhance the health of cultured species and the quality of seafood for consumers.
- Use of environmentally compatible feed additives to improve gut microbiota, increase resistance to pathogens, and promote overall animal health.
- Reduction in the use of fish meal and fish oil in mariculture.

Circular bioeconomy approaches

- Valorization of mariculture waste into biofertilizers or sustainable aquatic feed ingredients.
- IMTA arrangements using filter-feeding bivalves or marine algae to recycle nutrients, improve environmental health, and surge profitability.
- Development of offshore mariculture farms. Even though costly, it can decrease ecosystem impacts compared to coastal mariculture farms, while sustaining high productivity.

Food safety and consumer health

- Ensuring the safety of mariculture products by implementing proper food handling and preparation of standards, creating awareness about the hazards related with consuming raw or under cooked seafood, and encouraging efficient post-harvest processing and preservation methods.

- Monitoring of pollutants (heavy metals, hydrocarbons, microplastics, antimicrobials and other chemicals) in farmed seafood.
- Implementation of international food safety standards and strategies to warrant safe trade and consumption.

Global associations and policy integration

- International cooperation for managing pathogens, AMR, and climate- and trade-related hazards in mariculture through the sharing of surveillance data and best practices
- Integration of socioeconomic and policy factors to ensure fair access, regulatory oversight, and long-term industry expansion.

Limitations

Despite increasing awareness of the 'One Health' framework, numerous limitations exist in its effective implementation to Indian mariculture. AMR, human health, and aquatic disease databases are not well integrated, and surveillance is still fragmented. Unavailability of enough data hinders the monitoring of chemical pollutants and microbial risks. Policy fragmentation across mariculture, environmental, and health sectors reduces coordination and response efficiency. Climate change causes an extra risk by increasing stress events that can trigger pathogens, emphasizing the requirement for predictive disease and climate models. Socioeconomic inequalities also exist, since small-scale farmers frequently lack access to diagnostics, biosecurity and quarantine measures, and expert supports. Current One Health research networks are split between microbiological and environmental health themes; greater interdisciplinary integration is needed to address emerging concerns like climate-health linkages, pollution, and environment-health indicators. The lack of uniform 'One Health' metrics to check mariculture sustainability is another lacuna. Recently, Stentiford *et al.* (2020) has defined a set of success metrics to evaluate application of one health lens for sustainable aquaculture practices and these metrics can be applied to inform national and international scientific and policy strategies.

Conclusion

As the country prepares to make significant advancements in the mariculture sector, it is essential that this growth is pursued in a sustainable and well-regulated manner. Since mariculture activities always require close interactions between cultured animals, environmental, and human health, incorporating 'One Health' plan can offer a unique strategy to achieve disease prevention, ecosystem conservation, and food safety which fall within sustainable blue economy plans. Accordingly, India-specific One Health strategies are essential to ensure long-term sustainability in mariculture practices. It includes strengthening pollution control and waste management strategies and laws, restrictions of chemicals including antibiotics use, and promoting ecofriendly farming practices. Technological advancements like IMTA, sustainable and ecofriendly feeds, prophylactics, therapeutics, and fish health management strategies, low-carbon mariculture systems in appropriate mariculture sites, offshore farms, renewable energy integration, and early disease warning tools are needed to achieve this. Research that explores linking microbial community dynamics with disease and water-quality indicators, tracing AMR gene flow across mariculture-human-environment interfaces, source tracking of diseases, developing climate-adaptive species, and adopting different stress ameliorating strategies can supplement to this framework. Additionally, improving multisectoral coordination, regional teamwork and implanting 'One Health' framework into national mariculture plans and regional blue economy strategies can be the keys. Capacity building programs through digital extension tools, participatory monitoring, and regional One Health training programs that can empower small scale farmers are also required. In conclusion, integration of one health framework can transform Indian mariculture into a robust, health-promoting nutritious food production system.

Estuarine Fisheries of India: Status, Threats and Pathways for Conservation

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Estuaries are vital, highly productive ecotones that serve as critical nursery and feeding habitats for global fisheries, providing essential services like coastal protection and carbon sequestration. In India, over 300 estuaries, including deltaic systems on the East Coast (e.g., Hooghly-Matla) and lagoon/ria-type systems on the West Coast (e.g., Vembanad), contribute about 6-8% of inland fish production, supporting key species like Hilsa, penaeid prawns, and mud crabs, and underpinning coastal livelihoods. However, these systems face severe threats from overfishing, pollution, habitat degradation (mangroves, mudflats), and hydrological alterations (e.g., dams like Farakka), which are compounded by climate change impacts. Sustainable management is pursued through national policies like the Coastal Regulation Zone (CRZ) and PMMSY, emphasizing the need for an ecosystem-oriented strategy that integrates conservation of habitats and resources with collaborative governance.

Indian Estuarine Systems: Habitat, Classification, and Importance

Indian estuaries are dynamic ecotones vital for ecological productivity, coastal protection, and fisheries, serving as critical breeding, spawning, and nursery habitats for numerous finfish and shellfish. India hosts over 300 estuaries, exhibiting significant variability in geomorphology and hydrology.

Habitat Status and Degradation

Indian estuarine habitats include mangroves, mudflats, seagrass beds, tidal marshes, and sandbanks, all crucial as nurseries for juvenile fish and crustaceans.

Degradation: These essential ecosystems face severe pressures from land reclamation, pollution, urban expansion, and unregulated aquaculture, leading to fragmentation and loss.

Mangroves: The estimated at 4,975 km², of mangrove cover has diminished in several areas, primarily due to conversion for aquaculture and agriculture, though states like West Bengal, Odisha, and Gujarat have initiated restoration programs.

Seagrass Beds: Systems like those in the Gulf of Mannar, Chilika, and Vembanad are stressed by eutrophication and sedimentation.

Mudflats and Sandbanks: These intertidal zones are modified by dredging, construction, and shoreline alterations.

Classification of Estuarine Systems

Based on geomorphology and hydrology, Indian estuaries are categorized into four main types:

a) Big Tide-Dominated Deltaic Estuaries

Distribution: Along the eastern coast (e.g., Ganges-Hooghly, Mahanadi, Godavari, Krishna, Cauvery).

Characteristics: Wide mouths, extensive intertidal zones, strong tidal influence, and high freshwater input.

Key Fisheries: Thrive on species like Hilsa (*Tenualosa ilisha*), catfishes, mullets, and penaeid prawns.

b) Lagoon and Backwater Systems

Distribution: Semi-enclosed systems (e.g., Chilika Lagoon, Pulicat Lake, Vembanad Backwaters).

Characteristics: Influenced by tidal exchange and monsoonal runoff; form unique interconnected systems (Vembanad is a Ramsar site).

Key Fisheries: Crucial for prawn, mullet, crab, and clam fisheries (*Paphia malabarica* in Vembanad).

c) Ria-Type Estuaries

Distribution: Along the western coast (e.g., Mandovi-Zuari, Netravathi-Gurupur).

Characteristics: Formed by submerged river valleys; exhibit high tidal amplitudes and significant salt intrusion during the dry season.

Key Fisheries: Support diverse benthic fauna (bivalves, crabs) essential for artisanal fishing.

d) Tiny Riverine Estuaries

Distribution: Smaller systems along the coast (e.g., Rushikulya).

Characteristics: Highly responsive to local environmental factors and seasonal fluctuations.

Ecological and Socio-economic Importance

Estuarine food webs are fundamental to the productivity of commercially important fisheries and the economic stability of coastal communities in states like West Bengal, Kerala, and Goa.

Commercial Species: Key resources include penaeid prawns (*Fenneropenaeus indicus, Metapenaeus dobsoni), mud crabs (Scylla serrata*), mullets (*Mugil cephalus*), catfishes, and Hilsa.

Socio-economic Role: Estuarine fisheries underpin artisanal and small-scale fisheries, providing essential protein, income, and employment, and are intricately linked to traditional livelihoods and cultural practices.

Status of Estuarine Fisheries

Estuarine fisheries in India exhibit multi-species and multi-gear dynamics with seasonal variations. Trends include localised declines in catch and size structure in heavily exploited areas, contrasting with seasonal fluctuations driven by monsoon hydrology and recruitment success in other systems.

The key estuarine systems in India, ranging from massive deltaic areas to smaller backwaters, face similar threats from human activities, despite supporting distinct and vital artisanal fisheries.

Key Estuarine Systems: Snapshot

Hooghly-Matla Estuarine System (West Bengal) is one of India's largest and most dynamic deltaic systems (northern arm of the Ganges-Brahmaputra-Meghna delta).

Key Fisheries: Rich diversity, including Hilsa (*Tenualosa ilisha*), mullets, catfishes, prawns (*Macrobrachium rosenbergii*, *Fenneropenaeus indicus*), and mud crabs.

Major Challenges: Altered freshwater flow from upstream barrages (like Farakka), industrial/municipal effluents, and dredging. These changes impact Hilsa migration and spawning. The lower estuary faces periodic hypoxia and heavy metal buildup.

Management Focus: Essential need to safeguard freshwater inflows and protect vital nursery habitats, particularly the adjacent Sundarbans mangrove creeks.

Habitat structure of lower part of Hooghly-Matlah estuarine system

Pulicat Lake (Andhra Pradesh/Tamil Nadu) is India's second-largest brackish water lagoon with an area of 450 km^2.

Intense fishing zones of Pulicat Lake

Key Fisheries: Economically important species like mud crabs (*Scylla serrata*), penaeid prawns, mullets, and edible bivalves

Major Challenges: Significant habitat reduction due to encroachment and aquaculture expansion. Heavy metal accumulation from industrial and catchment pollution poses risks to ecosystem health and human consumption.3

Management Focus: Thorough monitoring, habitat restoration, and adaptive, community-based approaches (e.g., rotational harvesting, size limits for crabs).

Vembanad Lake (Kerala) is India's longest backwater system (2033 km^2) and a Ramsar-designated wetland.

Key Fisheries: Supports notable artisanal fisheries, clam (*Paphia malabarica*) and prawn farming, and tourism.

Major Challenges: Hydrological interventions (like the Thanneermukkom barrage), reclamation activities, nutrient enrichment, and effluent discharge causing fluctuations in fish catches.

Management Focus: Strategic zonal planning and balancing conservation with socio-economic needs through collaborative governance.

Mandovi-Zuari Estuary (Goa) is Ria-type estuary (smaller but crucial for local communities).

Key Fisheries: Penaeid prawns, mud crabs, mullets, and small finfishes targeted by artisanal fishers.

Major Challenges: Over-exploitation of juveniles via small-mesh nets, and habitat deterioration from port development and sand extraction, negatively impacting productivity.

Management Focus: Implementing sustainable strategies like regulating mesh sizes and habitat conservation.

Rushikulya and Netravathi-Gurupur Estuaries (Smaller Systems)

Rushikulya (Odisha) serves as a prime example of a seasonal fishery highly linked to monsoonal freshwater inflow. Challenges include upstream water extraction and agricultural runoff altering salinity.

Netravathi-Gurupur (Karnataka): Experiences changes in catches due to urban development in Mangalore and port infrastructure, affecting tidal flushing and nutrient availability. Management Focus: These smaller systems require localised monitoring and adaptive management strategies tailored to their distinct hydrological dynamics, including controlling land-based pollution and protecting essential habitats.

Species of commercial and conservation concern

Key estuarine species in India are crucial for both commercial value and conservation focus due to their role in coastal food security and artisanal livelihoods. The most valued finfish is Hilsa (*Tenualosa ilisha*), found in deltaic systems like the Hooghly-Matla. Hilsa is highly susceptible to overfishing and environmental changes, particularly those affecting river connectivity and spawning migration. Other important finfish include mullets, anchovies, and catfishes. Among crustaceans, mud crabs (*Scylla serrata*) and penaeid prawns (*Fenneropenaeus indicus, Metapenaeus dobsoni*) are heavily exploited for both domestic and export markets.

The productivity of these species is sensitive to habitat degradation, salinity changes, and pollution, necessitating stringent management strategies, including the regulation of harvest practices and ensuring sufficient riverine-estuarine connectivity for successful spawning and recruitment.

Issues Facing Estuarine Fisheries in India

Estuarine fisheries in India face a range of critical, interconnected challenges that compromise ecological integrity and resource sustainability:

- Overfishing & Destructive Practices: Widespread use of small-mesh, non-selective gear causes significant juvenile bycatch (e.g., Hilsa and prawns), reducing stock recruitment and resilience. Prawn trawling also damages benthic habitats.
- Habitat Loss and Degradation: Essential nursery habitats—mangroves, intertidal flats, and seagrass beds—are lost or fragmented due to reclamation, dredging, urban development, and unregulated aquaculture. This alters bathymetry and hydrodynamics, affecting species abundance (e.g., clams and prawns in Vembanad).
- Water Quality Decline (Pollution): Point and non-point sources (industrial effluents, sewage, agricultural runoff) lead to eutrophication, hypoxia/anoxia, and the accumulation of heavy metals and pollutants in sediments and biota (e.g., Pulicat Lake, Hooghly-Matla), impacting species survival and human consumption safety.
- Modifications in Water Flow: Dams and barrages (e.g., Farakka Barrage) significantly reduce freshwater inflows, altering crucial salinity gradients. This disrupts the spawning migrations and recruitment of key species

like Hilsa, severely impacting fisheries productivity (e.g., Narmada Estuary).

- Climate Change and Sea-Level Rise: Changing monsoons, rising temperatures, and sea level rise influence salinity patterns and species distribution. Increased severe weather events (cyclones) destroy habitats and fishing infrastructure.
- Invasive Species and Disease: The introduction of non-native species can alter community structure. Furthermore, frequent disease outbreaks in intensive aquaculture reduce stocks of prawns, crabs, and finfish.

These pressures collectively pose considerable threats, making thorough, integrated management essential for long-term sustainability.

Approaches for safeguarding, overseeing, and enacting policies

A successful strategy for estuarine management in India requires a comprehensive approach integrating ecological science with social equity:

Key Management and Policy Approaches

- Ecosystem Protection & Rehabilitation: Protect and restore essential habitats (mangroves, intertidal zones) through community-driven afforestation and engineering. Establish no-take zones to protect critical nursery and feeding grounds, enhancing juvenile survival.
- Fisheries Regulation: Enforce sustainable practices through mesh-size regulations, seasonal closures (aligned with spawning), and restrictions on harmful gear. Use collaborative management frameworks to engage fishers, improving compliance.
- Pollution and Watershed Control: Maintain water quality by improving wastewater treatment, controlling agricultural and aquaculture runoff, and enforcing environmental compliance for coastal industries.
- River Basin Flow Integration: Implement environmental flow releases at the basin level to maintain natural salinity patterns in downstream estuaries, which is vital for migratory species and ecosystem health.
- Monitoring and Research: Establish long-term monitoring of fish stocks, water quality, and habitat conditions (e.g., mangrove cover). Deploy early-warning systems for hypoxia or pollution events to mitigate fish mortality and public health risks.
- Policy and Collaboration: Promote cross-sectoral planning by integrating fisheries, coastal zone management, pollution control, and river basin authorities. Strengthen local institutions and support adaptive management.
- Community Engagement: Reduce resource strain by promoting livelihood diversification (e.g., regulated mariculture, ecotourism) and encouraging participatory governance.

These three case studies—Pulicat Lake, Hooghly-Matla Estuary, and Vembanad Lake—collectively underscore essential strategies for sustainable estuarine fisheries management in India.

Pulicat Lake (lagoon, AP/TN): Faces habitat loss, heavy metal pollution, and encroachment. It demonstrates the effectiveness of community-based fisheries management (e.g., crab harvest limits) and the value of combining local knowledge with scientific monitoring to sustain livelihoods.

Hooghly-Matla Estuary (deltaic, WB): Highlights the direct link between upstream catchment health (damming, pollution) and downstream impacts (altered salinity, Hilsa migration decline). Its management requires cohesive, catchment-integrated strategies that span administrative borders.

Vembanad Lake (backwater, Kerala): Illustrates the complex balance needed among tourism, aquaculture, and artisanal fisheries. Success depends on strategic zonal planning, controlled aquaculture, and multi-stakeholder collaboration to balance socio-economic needs with conservation priorities.

In summary, these estuaries prove that participatory governance, scientific assessment, and integrated catchment-level planning are critical for the long-term resilience of India's estuarine ecosystems and the communities dependent on them.

To ensure the sustainable management of Indian estuarine and coastal fisheries, the following strategic actions are prioritized, balancing ecological integrity with socio-economic welfare:

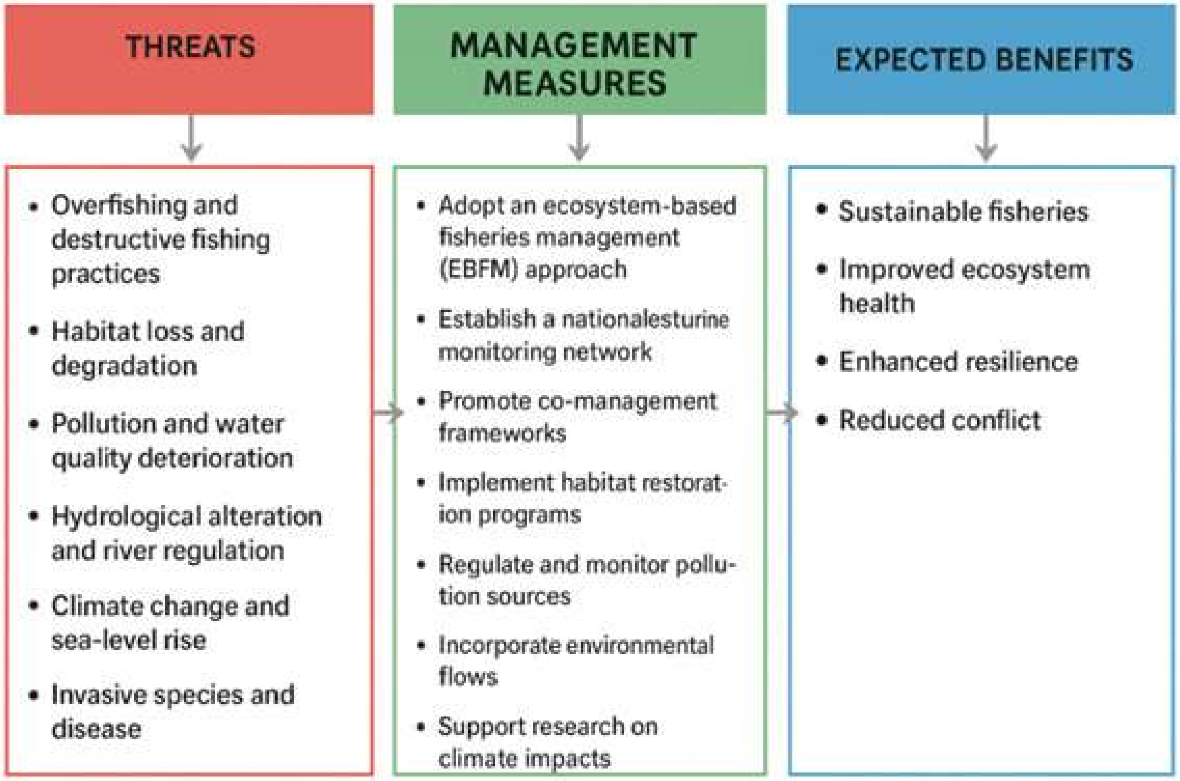
- **Ecosystem-Based Management** (EBM) & Monitoring: Implement an EBM strategy that considers species interactions and habitat, supported by a national monitoring network for fisheries data, water quality, and habitat health.
- **Habitat Restoration & Protection**: Execute focused restoration initiatives for critical nursery habitats,

primarily mangroves and seagrass beds.

- **Pollution Control & Regulation**: Enforce stringent effluent treatment standards and conduct routine compliance checks on all pollution sources.
- **Integrated Water Management**: Integrate environmental flows (e-flows) into the operation of upstream dams and barrages to maintain natural salinity gradients and support migratory species.
- **Co-Management and Governance**: Encourage co-management frameworks to empower local fisher communities with significant decision-making authority and improve regulatory adherence.
- **Climate Change Adaptation**: Investigate climate change effects and develop adaptive strategies focused on vulnerability assessments specific to key estuarine species.
- **Livelihood & Value Chain Enhancement**: Enhance market and value-chain strategies to minimize post-harvest losses and improve fisher incomes, simultaneously promoting sustainable fishing practices.

Conclusions

Indian estuaries are vital for fisheries, biodiversity, and coastal livelihoods, but face significant, escalating threats from human activities and climate change. Their sustainable future hinges on an organized, interdisciplinary management strategy that unifies habitat protection, fishery regulation, pollution control, community involvement, and data-driven monitoring. The current critical juncture demands a shift from disjointed efforts to a cohesive, ecosystem-focused approach. Investing in scientific inquiry, improving governance, and engaging local communities are crucial steps to ensure the long-term health and productivity of these essential ecosystems and achieve truly sustainable "Blue Growth."



Flow-chart showing threats, management measures and expected benefits of Indian estuarine system

Creating a Seaweed Value Chain in India: The Role of High Value Products

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Seaweeds, often referred to as the "ocean's green gold," are renewable marine resources with significant economic and ecological potential. They serve as rich reservoirs of bioactive compounds and can be utilised to develop a wide range of high-value products for applications in the food, agriculture, pharmaceutical, cosmetic, and biotechnology industries. Seaweeds play essential ecological roles by supporting biodiversity and enhancing the stability and productivity of marine ecosystems. Globally, approximately 7,000 species of red algae (Rhodophyta), 2,000 species of brown algae (Phaeophyceae), and 1,800 species of green algae (Chlorophyta) contribute to this diversity (Jayasankar, 2024). Seaweed cultivation is practiced extensively in nearly 61 countries. Among the 221 species of commercial importance, around 145 are utilized for human consumption as direct food (Xie *et al.*, 2024). Extensive coastline and favourable oceanic conditions in India provide an excellent opportunity to develop a strong seaweed-based industry. However, to fully utilize this potential, there is a need for a well-organized and scientifically managed seaweed value chain that covers all stages from cultivation to post-harvest handling. The post-harvest handling diversified into processing, innovation, and sustainable marketing. Creation of high-value seaweed-based products rich in bioactive compounds not only offers great commercial promise but can also improve the livelihoods of coastal communities and contribute significantly to the country's economic development.approximately 11098.81 km. A survey conducted by the ICAR-Central Marine Fisheries Research Institute (CMFRI) has identified about 23,970 hectares along this coastline as suitable habitats for the cultivation and natural growth of diverse seaweed species (Ganesan *et al.*, 2019; Pandey *et al.*, 2024). These natural advantages offer vast opportunities for developing a strong seaweed industry in the country. The CMFRI estimated 72,385 tonnes of seaweed production in 2023, with *Kappaphycus alvarezii* and *Gracilaria edulis* being the dominant species under cultivation. Seaweed cultivation is prevalent in Tamil Nadu, Gujarat, Lakshadweep, Andaman & Nicobar Islands, Andhra Pradesh, and Odisha. In recent years, focused government initiatives and technological advancements have expanded cultivation into new coastal areas, resulting in an increase in production from 18,890 tonnes in 2015 to 74,083 tonnes in 2024. The current prospects of seaweed farming and value addition in India are shown in Fig. 1. Globally, countries such as China, Indonesia, South Korea, and the Philippines dominate seaweed production, collectively contributing around 97% of total global output. According to FAO data, 97% of global seaweed production is obtained through aquaculture. In contrast, India's contribution is only about 0.01%, which is negligible compared to its vast coastline, highlighting the serious underutilization of marine resources.

Recognizing this immense potential, the Government of India launched the Pradhan Mantri Matsya Sampada Yojana (PMMSY) in June 2020, with an investment of nearly ₹20,050 crore to enhance the fisheries and aquaculture sectors. Within this framework, seaweed farming has been prioritized as a key growth segment, and the Union Government has recognized commercial seaweed cultivation as a 'sunrise sector' under the PMMSY (Dineshkumar *et al.*, 2025). The scheme has provided significant funding and institutional support for seaweed development initiatives across the country. Notable achievements include the establishment of a Multipurpose Seaweed Park in Tamil Nadu, a Seaweed Brood Bank in Daman and Diu, and a Centre of Excellence for Seaweed at Mandapam, Tamil Nadu. In addition, guidelines for the import of live seaweed have been introduced to facilitate the introduction of new species and enhance cultivation practices. In October 2024, the Government of India issued the "Guidelines for Import of Live Seaweeds into India" to enable the import of high-quality live seaweed and germplasm. This initiative aims to enhance domestic production and promote the growth of the seaweed industry and coastal economies, while implementing stringent biosecurity measures, including quarantine protocols and risk assessments, to protect the environment.

Seaweeds play an increasingly important role as raw materials in functional foods, fertilizers, pharmaceuticals, cosmetics, animal nutrition, and emerging bioenergy technologies. To harness this potential, the government is actively promoting seaweed farming in key regions such as the Gulf of Kutch and Kori Creek, in collaboration with state fisheries and research institutions. A successful farming initiative was launched in Chetlath Island, Lakshadweep, by the ICAR–CMFRI Mandapam Regional Centre, where six plots, each containing 100 tube nets, were established with the active participation of unemployed women, resulting in a harvest of 15 tonnes of seaweed within 45 days. Technological advancements have significantly strengthened India's seaweed sector. These include tissue culture techniques for mass production of high-quality, disease-resistant seed material, Integrated Multi-Trophic Aquaculture (IMTA) systems that integrate seaweed cultivation with other aquaculture practices, and the use of GIS and remote sensing technologies to identify suitable farming zones. Additionally, the adoption of diverse farming structures such as PVC net cages, PVC rafts, and bamboo rafts has accelerated the growth of India's seaweed economy. However, despite this potential, India's seaweed sector remains underdeveloped and fragmented in a few coastal regions, such as Tamil Nadu and Gujarat, with limited downstream processing and value addition. Creating a robust value chain that connects seaweed farmers, processors, industries, and markets is therefore crucial for realizing the sector's full potential and generating sustainable coastal livelihoods.

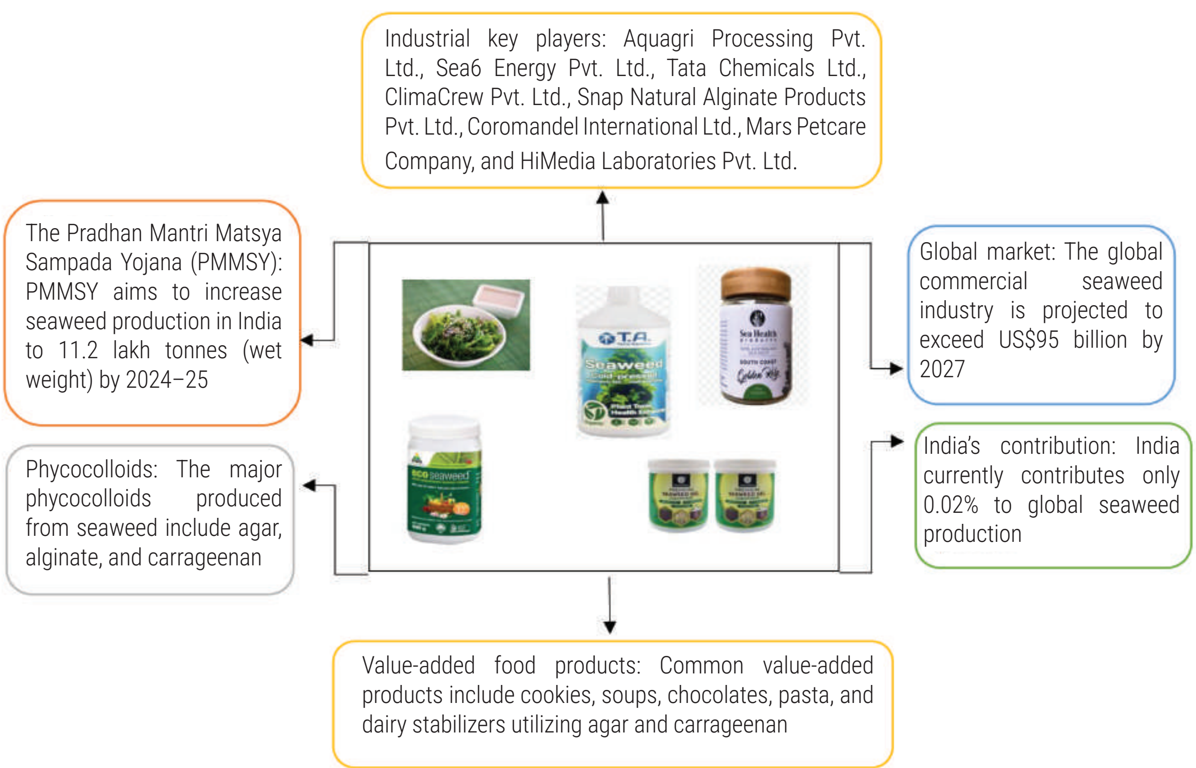

Fig. 1: Current prospects of seaweed farming and value addition in India
Reference: Jaikumar et al. (2024)

Seaweed value chain and its significance

The seaweed value chain plays a crucial role in promoting economic growth, livelihood improvement, and environmental sustainability, particularly in coastal regions where seaweed serves as an important source of income (Mario, 2024). It includes every stage from seed selection and cultivation to harvesting, processing, marketing, and export. Each link of the supply chain needs to be efficient to minimize waste, maintain quality, and enhance profitability. The process begins with the establishment of hatcheries and nurseries to supply quality seedlings of fast-growing seaweeds, such as Kappaphycus sp. And Gracilaria sp. Efficient harvesting, drying, storage, and transport systems are vital for preserving quality and reducing post-harvest losses. Processing facilities and biorefineries enable the extraction of valuable compounds like carrageenan, agar, alginate, and other bioactive substances used in food, pharmaceuticals, cosmetics, fertilizers, animal feed, and biofuels, thereby creating diverse market opportunities. Strong marketing channels and value addition strategies that link farmers with industries can help in ensuring fair pricing and higher incomes. Supportive government policies, cooperatives, and partnerships can strengthen infrastructure, training, and financial access. A well-integrated seaweed value chain not only increases productivity and income but also fosters innovation and sustainable coastal development.

The Seaweed Value Chain in India: An Overview

A value chain encompasses the full range of activities involved in bringing a product from conception through production, processing, to delivery to the final consumer. In the case of seaweed, the process involves multiple stages, ranging from cultivation to the production of high-value products for various industries. A seaweed value chain typically involves five key stages, including cultivation and harvesting, post-harvest handling, extraction and processing, value-added product development, marketing and distribution. At present, most Indian seaweed farmers remain at the first and second stages, selling dried raw material to intermediaries at low prices. The key to enhancing profitability lies in moving up the value chain.

Value Chain for Raw and Dried Seaweed

The value chain for raw seaweed represents a series of interconnected activities and stakeholders involved in moving freshly harvested seaweed from farms to the final markets. This chain covers essential stages such as input supply, cultivation, post-harvest handling, trading, and marketing, which involve active collaboration of seaweed farmers, cooperatives, traders, and government institutions to ensure efficient production and distribution. Freshly harvested seaweed in India is primarily used for re-seeding and as raw material for processing into dried seaweed and higher-value products such as carrageenan, agar, fertilizers, and animal feed. Direct local consumption is limited. The value chain is depicted in Fig. 2. The dried seaweed value chain forms the backbone of commercial seaweed trading, especially for industrial uses such as carrageenan and agar extraction. The stages involved in this chain involve input supply, cultivation, post-harvest handling, processing, trading, and marketing.

Seaweed-based High-Value Products

Transforming seaweed into high-value products is a crucial step in developing a sustainable and profitable seaweed industry. Adding value through advanced processing techniques can significantly enhance market potential. Modern technologies enable the extraction of bioactive compounds from seaweeds, such as fucoidan, fucoxanthin, agar, carrageenan, alginate, and phlorotannins, which possess antioxidant, anti-inflammatory, antidiabetic, and anticancer properties (Cotas *et al.*, 2024). Seaweeds are rich in proteins, polysaccharides, polyphenols, vitamins, minerals, and PUFAs, making them highly valuable for health and nutrition. These compounds are utilized in supplements, nutraceutical powders, fortified foods, and functional food products, including snack bars, cookies, beverages, yoghurt, cheese, and nutri-drinks. Pharmaceutical applications include antiviral, anticancer, anti-inflammatory, anticoagulant, and immune-modulating properties. For example, fucoidan, carrageenan, and alginate reportedly inhibit viruses, while fucoidan and phlorotannin exhibit anticancer activity. Seaweed extracts also support wound healing, cardiovascular health, and drug delivery (Pandey *et al.*, 2024). In addition to macro-minerals, seaweeds are a rich source of trace elements such as iodine, iron, manganese, copper, and zinc, which can be utilized as health supplements.

Seaweed-derived active compounds are widely used in cosmetics for their antioxidant, antibacterial, anti-ageing, anti-acne, and moisturizing properties. In cosmetic formulations, seaweed extracts provide hydration, anti-ageing, UV protection, detoxification, and soothing effects. Rich in polysaccharides, seaweed acts as a powerful humectant, drawing moisture to the skin and providing long-lasting hydration. Products include creams, serums, masks, cleansers, toners, and facial gels, supporting the development of sustainable cosmetic products (López *et al.*, 2021). Seaweed is also a sustainable source of biofuels (bioethanol, biodiesel, biohydrogen) and bioplastics, as it grows rapidly without requiring arable land or freshwater. Biopolymers such as alginates, carrageenan, and ulvans are utilized in biodegradable and eco-friendly packaging materials (Hemavathy *et al*., 2025). Seaweed-based fertilizers and bio-stimulants are recognized for their ability to enhance sustainable agriculture, increase crop resilience, and support organic and regenerative farming systems. Rich in over 60 minerals and trace elements not found in land plants, seaweed is a valuable soil conditioner and biofertilizer. Its extracts improve plant growth, boost productivity, and enhance resistance to pests and fungal diseases. Liquid seaweed fertilizers are widely used in organic farming and horticulture to improve crop quality and yield (Jayasankar, 2024). Other emerging high-value applications include animal feed supplements, aquaculture feed additives, and hydrogels for biomedical applications, further broadening the market potential of seaweed. In essence, value addition transforms seaweed from a simple coastal crop into a versatile resource with wide-ranging applications in food, pharmaceuticals, cosmetics, bioenergy, bioplastics, and sustainable agriculture, while promoting economic resilience and environmental sustainability.

Value chain for high-value seaweed products

Table 1: Overview of the seaweed value chain for high-value applications

Functions	Activities	Key Operators / Actors
Input Provision	Supply of seedlings, farm materials, and training	Seed suppliers, cooperatives, agri-shops
Production	Farming, maintenance, harvesting	Farmers, farmer groups
Post-Harvest	Cleaning, drying, grading	Farmers, cooperatives
Processing	Extraction of bioactive compounds, formulation of high-value products	MSMEs, processors, R&D units
Trading & Marketing	Branding, distribution, export	Traders, exporters, cooperatives
End Market	Food, cosmetics, nutraceuticals, biofertilizer, and bioplastic sectors	Domestic and international buyers

The high-value seaweed value chain encompasses both upstream and downstream activities. Upstream processes include cultivation, seeding, maintenance, harvesting, and initial post-harvest treatments such as drying. Downstream activities focus on processing the dried seaweed into high-value products like carrageenan and bioactive compounds for pharmaceuticals, nutraceuticals, and cosmetics, followed by marketing, trading, and distribution to end consumers.

Conclusion

Creating a seaweed value chain in India holds immense potential for the country's coastal economy and sustainable development. High-value seaweed products, including nutraceuticals, pharmaceuticals, cosmetics, biofuels, bioplastics, agricultural products, etc., can drive economic growth by adding substantial value to seaweed. Strengthening this sector requires coordinated policy support, infrastructure development, investment in research and institutional frameworks. Ultimately, leveraging seaweed's diverse applications will empower coastal communities, boost livelihoods and position India as a global leader in the blue economy.

India's Blue Economy in Twenty First Century: Navigating through the Triple Planetary Crisis

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India has been a maritime nation since centuries. Ancient trade routes through India's northern parts have been complimented with sea routes supported by contemporary prominent ports dotted through its coastline that stands at 11,000-odd km as per the latest calculations. This has been possible due to unique geographic feature of the Indian peninsula, along with the numerous islands that together puts her at the 18th largest Exclusive Economic Zone (EEZ). Being centre-stage of global economy that every nation wanted to trade with, and chart new course through the sea if needed, it was inevitable that one of the world's three major ocean basins has been named after India. It is in these context that this souvenir article explores the future course of India's blue economy, and marine fisheries, in the backdrop of impending triple planetary crisis to which the nation itself has hardly been contributed to.

India's share to world GDP reached as high as an estimated 30%, and always stayed above 20% until mid-18th century. Thus, it is only pertinent that in the post-independence era, India has been striving to shed the colonial-era constrains to bring back ocean economy to the fore, which at present contributes to less than 5% of national GDP. The present share comes chiefly from limited sectors viz. trade transport, energy extract, and fisheries. For the former two, there have been significant achievements already made e.g. policy consciousness in being situated at global maritime superhighways, handing more than 90% of its own trade through sea while working towards becoming cargo handling hub similar to having established significant oil and gas refining capabilities. While the latter – i.e. marine fisheries – is at the crossroads of scaling up capacity and sustainability, because it supports 3-4% of the country's population. However, the industry is largely capture fishery and rather an individual affair, with almost two thirds of the fisher being under poverty. Growth of marine fisheries sector is also imperative considering food security and the protein requirement of young demography of a nation that is world's most populated, but ranks seven in the land area. India has successfully charted its own path through green, white and yellow revolutions. The blue economy is greatly dependant on sustainable ocean use and stands in stark contrast of 'brown' economy which refers to the unwise model of exploiting natural resources.

Triple Planetary Crisis

The crisis in the bouquet term "triple planetary crisis" are - climate change, loss of biodiversity, and pollution. These three create intertwined challenges that affect survival and sustenance of the mankind on this planet. This is remarkable for a species that has a fractional share in the earth's geological time-scale and yet, has driven the changes in the land-use and atmosphere of a planet at a scale that no other biotic factor has demonstrated yet. The fact that the term is not being merely a catchphrase in nature, but rather adopted as a formal recognition under and across the United Nations system, is a mark of the impending urgency towards the real and present danger.

Climate change

In the beginning of twenty-first century, there has been a reckoning that started percolating across various strata of society and governance around the world that climate change is not only real but largely inevitable for its parts at least (Fig.1). India has been one of the lowest contributors of the greenhouse gases (GHGs) which are proven responsible for climate change, with overall national GHG emissions reaching only to about 5% of the global. Considering that every sixth human on this planet is an Indian, it is no wonder that India's per-capita emissions stand at less than half of the global average. On the other hand, it is an undeniable fact that India can not be denied moving forward to the economic upturn in order to improve lives, lifestyle and livelihood. Pursuing this target India has lifted more than two third of its poor population out of poverty in recent decades. Despite these two contradictory circumstances, India has been a vocal and active demonstrator of GHG emission reduction efforts. India's GHG contributions chiefly come from fossil fuel usage, with agriculture sector being at a distant second.

In that backdrop, usage of satellite data and prediction methods to guide India's fisher in the hostile marine theatre, has been one important intervention which addressed to both of the aforementioned categories of GHG emissions. Other interventions include usage of cleaner fuel options (e.g. LNG) for cargo vessels to solar powered fishing boats, which are at various stages of development and adaptations. The same is to be applied to the post-harvest sector where cooling plants, storage and transportation could follow the suit. It is evident that India is also at the receiving end of the climate led disruptions despite not being a major contributor itself. Events such as loss of glaciers or landslides at tourism hubs in lower Himalayas, or flash floods in metro cities gets attention in the media nationwide. On the other end, erratic monsoon spells or land erosion do affect to freshwater fisher as much as any other farmer, while impacts such as loss of fishing days and elevated occupational hazards due to frequent and intense rough sea-state, or the erosion of the beach slope that cuts off access to sea for small fisher do not get reported beyond local news.

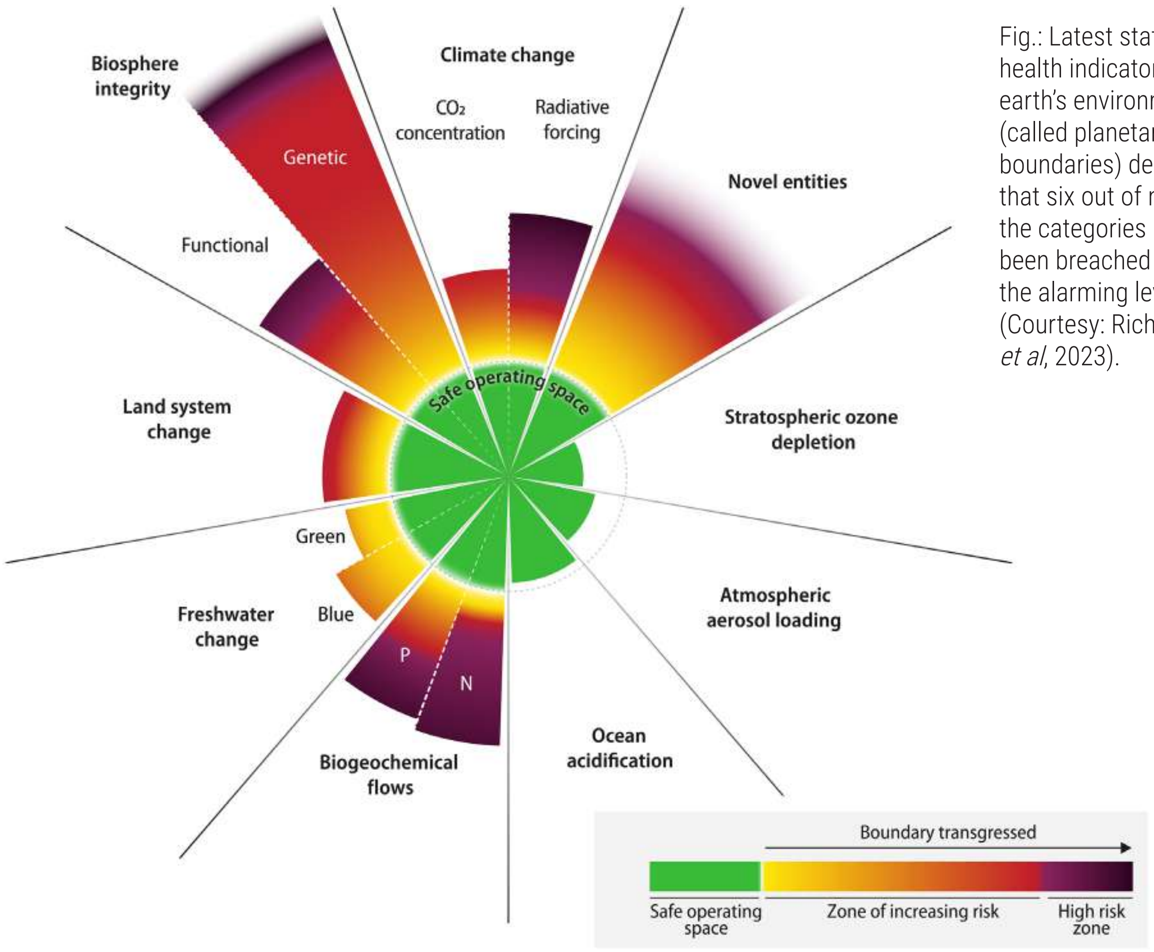

Fig.: Latest state of the health indicator of the earth's environment (called planetary boundaries) depicts that six out of nine of the categories have been breached to the alarming levels. (Courtesy: Richardson *et al*, 2023).

The Indian Ocean is unique in terms of Eurasian landmass disconnecting it with the north pole. Since the entire northern Indian Ocean is situated within tropics, it is subjected to distinct monsoon reversal pattern which not only creates a monsoon season for the land agriculture, but also produces reversal of the coastal currents along the Indian coast. Accordingly, the onset of monsoon, resultant current, its strength and associated biogeochemistry determine the supply of food for the coastal fish stocks, survival of larvae and thus, success of recruitment. In terms of fishing grounds, they vary spatio-temporally due to absence of both - a western boundary current as well as an eastern boundary upwelling system (EBUS) – known to support some of the world's major fisheries. As a result, both of the northern Indian Ocean basins (Arabian Sea. and Bay of Bengal) manifest a quasi-stagnant water mass that support a semi-permanent oxygen minimum zone (OMZ) throughout the year. This translates into a shrunken habitat for commercially important fishes such as tuna (Nimit *et al.*, 2020). Further, teleconnections and impact of met-ocean conditions in other basins viz. El Niño-Southern Oscillation (ENSO) or Atlantic meridional overturning circulation (AMOC) have been known to impact this region through perturbations in coastal currents, triggering marine heatwaves, to name a few.

Pollution and Biodiversity Loss

Both the climate impacts as well as the pollution, affect to the biodiversity. The Indian EEZ is not insulated from such effects either. Being situated at the maritime superhighway has its own demerits to fisheries sector which have been evident from the aspects such as maritime security (whether piracy or illegal, unreported, unregulated (IUU) fishing) or pollution causing accidents (e.g. X-Press Pearl) in the neighbourhood. The pollution in the marine environment often gets focused through the mainstream media reports on plastic or oil pollution or sometimes, for heavy metals. However, other types of pollutions such as (but not limited to) light and sound in the marine environment are inadequately understood. In that context, it is a much unknown territory even for researchers to estimate what would be the impacts coupled with climate change scenarios. The biodiversity loss is a considerable threat. However, researchers agree that till date we have been able to document only a fraction of marine life that exists. In other words, without exaggeration it is often said that we know more about the other side of the moon than the oceans around us beyond merely 200 meters. Earlier this year, The Nippon Foundation-Nekton Ocean Census announced discovery of more than 800 new species. Such instances establish that the anecdotes may be closer to reality than fiction. It should be however of our common concern that none of these expeditions were in the Indian Ocean, which is already less studied and understood in compare to the Atlantic or the Pacific. Even with the present known species, discovery or cataloguing is just a first baby step. Only a limited number of species have been studies thoroughly to understand their role in the ecosystem. In such a condition, it is highly uncomfortable takeaway that we may be losing more species from the marine environment before we discover them or understand climate implications fully. Such lost species could mean a wealth of genetic treasure lost forever which had potential to enlighten us from evolutionary processes to biomedical discoveries, i.e. aspects that are linked to existence and well-being of our own future generations.

Mitigation Measures

Global status

It is indeed, not an intention to claim that the situation is all bleak and there is no effort or hope. Researchers around the globe have been able to nudge policy makers through various forums that have resulted into the platforms that were non-existent earlier. It is worth to mention that the present decade (2021-2030) has been recognized as UN Decade of Ocean Science for Sustainable Development. This is certainly the highest attention that we have given to ocean sciences. Contrary to the popular belief or understanding of a decadal celebration, the UN Ocean Decade is aimed towards creating momentum to accelerate ocean science by 2030, rather than formally ceasing the activities at the end of the decade. Immediate such transition will be catered through the International Decade of Sciences for Sustainable Development (2024-2033). During the UN Ocean Decade, an array of activities has reached to manifold in compare to the previous decade. Targets such as 30x30 (an initiative under Kunming-Montreal Global Biodiversity Network) are being pursued by the stakeholders together, under which it is aimed that at least thirty percent of the land and ocean around the globe will be legally protected. Another such advancement is the UN Convention on the Law of the Sea (UNCLOS) led Biodiversity Beyond National Jurisdiction (BBNJ) Agreement (or the High Seas treaty) that aims to conserve and sustainably use marine biodiversity (including but not limited to recognized fisheries resources) in the areas beyond national jurisdictions (ABNJ). Of the minimum 60 ratifications required for the treaty to become legally binding all the nations, Morocco's ratification on 19 September 2025 has helped reach the mark, resulting into the treaty coming into the force on 17 January 2026.

Indian Efforts

Apart from the international or transboundary efforts, many countries have taken steps towards marine spatial planning within their EEZs. This is aimed at regulating economic activities while ensuring sustainability for the nation's economy. India has drafted its blue economy policy (BEP) with a note by the Hon'ble Prime Minister of India aptly summarized as "The Blue Economy of India is as important and at centre-stage for us as the blue chakra in our national flag". India's draft BEP enlists seven priority areas of which 'Coastal Marine Spatial Planning and Tourism' and 'Marine Fisheries, Aquaculture and Fish Processing' have been identified as independent priority areas. It is in that context 'India's Blue Economy: Strategy for Harnessing Deep-Sea and Offshore Fisheries' released by NITI Ayog in October, 2025 is a well-timed step taken in the direction of meeting India's fishery sector transformation aspirations.

Ocean Education: A Pressing Need

The policy documents provide first step towards a deep-thinking process involved by the nation and its stakeholders. Such documentation process in consultative in nature and attempts to cover important aspects, but nevertheless prone to underrepresent or omit some aspects. One such aspect is of capacity development, especially in the Indian context. As indicated by the last published Global Ocean Science Report (GOSR) 2020, the total ocean science researcher headcount is less than one thousand. This is a very underwhelming number for the world's most populated nation aspiring to tap its blue economy potential. It is no surprise that this is also reflected in the regional proportion of early-career researchers (ECR, who obtained their last degree in less than 10 years before), in which central and southern Asia region accounts for only 2% of their ocean researchers to be ECR – a number comparable to Northern Africa and Western Asia, and only ahead of Sub-Saharan Africa (1%).

These numbers are of course result of a mixture of systematic obstacles, some being technical whereas others being socio-economic (IOC-UNESCO, StOR, 2024). Data access for pursuing ocean science is often considered as an obstacle, which few countries such as India have been able to overcome to an extent by establishing National Oceanographic Data Centre (NODC). However, implementation of FAIR (Findable, Accessible, Interoperable, Reusable) data principles is a continuous process that involves all the stakeholders, and can not be achieved only by the NODC since it may not be the agency that generates all types of data that it holds or offers. Data generation is further complicated since majority of the ocean research in the Indian context is taken up in the coastal environment. Here, however, it is important that the coastal communities are kept at the centre stage by following CARE (Collective benefit, Authority to control, Responsibility, Ethics) data principles. It is inevitable for India to have more number of ocean research vessel with a strategy to sustain them as a national resource, rather than the sole responsibility of the agency that puts administrative and financial efforts in managing the same. Innovative solutions that reduces ship-based efforts must be welcomed, but the managers need to understand that the research vessels can not and should not be overruled in the process. Lastly, all types of research programs and projects should aim to build data repository that feeds to the long-term time-series data instead of a standalone effort with limited time-period. Then only we can ensure that the data that we 'earn' in that process can withstand FAIR and CARE data principles, and that those can help India achieve the very resilience it desperately needs in the wake of climate induced uncertainties.

Conclusion

The economy of India economy has ever been of importance to the global one and the Oceans play inseparable part into it. At the same time, the mankind is facing challenge to its own survival and well-being due to the combination of threats called triple planetary crisis. In order to address these challenges, at least to start with there are ample mechanisms at global scale as well as within the national policy pathways. These can be foundation to build upon further robust system to ensure 360-degree sustainable development. However, India needs to find ways for resource allocation towards ocean sciences at the scale manifold than present and the nation can not afford anymore to do this at a slower pace. In other words, the business as usual will not let the business to run as usual, let alone flourish. The resource allocation is needed to be focused on ocean research as well as education, with special attention to the fisheries sector, not only to find resource exploitation pathways but also towards conservation, so to ensure that the blue economy does not repeat the mistakes of the brown economy model. India does not lack foundation to achieve this. It only needs as a nation to break out of the cubicle of conventional perception, in order to realize its full potential.

Conservation, Management and Sustainable Utilization of Coastal Ecosystems: Initiatives from ICAR- CCARI, Goa

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Agriculture and allied sectors—including livestock and fisheries—remain vital to India's economy. As of 2023-24, about 46.1% of India's workforce is employed in agriculture and allied activities. The sector contributes around 18% to the country's Gross Value Added (GVA). Food grain production has grown sharply: from about 184.3 million tonnes in 1993-94 to 332.3 million tonnes in 2023-24. However, per-capita cereal consumption has declined over the same period—with monthly per-capita cereal consumption falling from 13.4 kg (rural) and 10.6 kg (urban) in 1993-94 to 9.4 kg (rural) and 8 kg (urban) in 2023-24. Without immediate corrective measures, per capita availability of food grains and essential nutrients will continue to deteriorate. India's coastal regions, stretching from Gujarat on the northwest coast to West Bengal on the northeast coast, harbor rich repositories of indigenous germplasm including cereals, pulses, fruits, vegetables, flowers, livestock breeds, and both inland and marine fish species. Integrated development of coastal agriculture encompassing these diverse components offers a promising pathway toward resource sustainability for coastal populations.

Significance and Characteristics of Coastal Zones

India's coastal zone spans 11,098.81 km of coastline across 9 coastal states, 4 union territories, and 65 coastal districts, supporting a population of 171 million people including 4 million engaged in fisheries. This region encompasses a 2.02 million km² Exclusive Economic Zone (EEZ), 43,230 km² of wetlands, and 4,991.68 km2, of mangrove forests, representing ecosystems of immense natural, cultural, environmental, and socioeconomic importance. The availability of extensive fertile land endows these zones with exceptional food and energy resource potential. However, they are characterized by a rain-fed agricultural system with seasonal extremes—excess water during monsoons and acute scarcity during pre-monsoon periods.

Agricultural, Livestockand Fish Diversity

Coastal regions demonstrate remarkable agricultural diversity, offering excellent conditions for rice-based cropping systems, horticultural plantations, and cultivation of high-value medicinal and aromatic plants. These ecosystems provide ideal environments for integrated farming systems incorporating aquaculture, dairy, piggery, poultry, and agroforestry. The Indian coastal states host over 13 cattle breeds, 5 buffalo breeds, 9 sheep breeds, 11 goat breeds, and more than 2,000 exploited fish species along the Indian coastline. Large-scale poultry and duck farming operations are concentrated in these coastal regions, contributing significantly to protein availability.Mangroves represent another critical natural resource along coastal areas, functioning as natural barriers against coastal erosion while providing firewood, fruits, fish, honey, and numerous other ecosystem services to coastal communities. As a broad interface between terrestrial and aquatic environments, the coastal ecosystem serves as a unique zone of biological productivity and diversity.

Challenges for the Coastal Agriculture

Despite their inherent potential, coastal regions face formidable agricultural challenges. Water-logging, seawater intrusion, soil salinity, salinization of groundwater table, and depletion of water resources due to over-extraction present persistent problems. Coastal soils typically exhibit poor moisture retention capacity, high nutrient leaching, weak base status, and low inherent fertility. Additional constraints include varying degrees of salinity, alkalinity, and acidity, along with iron toxicity or deficiency and impeded drainage systems.

Livestock and fisheries sectors face distinct challenges including low productivity in milk and meat production, overexploitation of fishery resources, diverse biotic stresses, progressive biodiversity degradation, and mounting impacts of climate change. The region's rich biological productivity faces rapid erosion due to deforestation, forest fires, and unplanned human settlements.

Vulnerability to Natural Disasters

Coastal zones represent highly fragile ecosystems particularly sensitive to climate change and natural calamities. Floods, cyclones, sand casting, and tidal waves occur with alarming frequency, devastating the economic prosperity of these regions. The east coast experiences greater vulnerability to such natural disasters compared to the west coast, resulting in recurring losses to agriculture, infrastructure, and livelihoods.

Knowledge and Technology Gap

A significant awareness gap exists regarding scientific farming practices and adoption of low-cost technologies among the agricultural communities in coastal regions. Bridging this knowledge divide through effective extension services, capacity building, and demonstration of sustainable practices remains essential for unlocking the full potential of coastal agriculture while ensuring environmental conservation and long-term sustainability of these vital ecosystems.

Initiatives of ICAR-Central Coastal Agricultural Research Institute

In recognition of the critical need for specialized agricultural research, education, and extension services in Goa, the Indian Council of Agricultural Research (ICAR), New Delhi, elevated the existing research complex to a full-fledged research institute in April 1989. Since its inception, the institute has conducted comprehensive basic, applied, and strategic research spanning field crops, horticulture, animal husbandry, and fisheries science. Research activities are strategically organized under five functional divisions: Natural Resource Management, Crop Science, Horticulture, Animal Science, and Fishery Science. Technology transfer programs reach farmers through both on-campus and off-campus training sessions, complemented by field demonstrations conducted in active collaboration with the Krishi Vigyan Kendra (KVK).

Mission and Mandate of the Institute

The Institute was started with a mission to achieve, "Introduction and improvement of all potential crops and various species / breeds of livestock and scientific exploitation of various aquatic resources for improving fish production". The mandate of the institute are the following.

- Researches on field and horticultural crops, livestock, and fisheries relevant to natural resource base of coastal India for sustainable productivity
- Develop climate resilient land use and farming systems for improved and sustainable livelihood through coastal agriculture
- Act as a centre of agro-eco-tourism

Research Achievements

Over the past 25 years, the institute has developed groundbreaking technologies for coastal agriculture. Significant achievements include comprehensive management protocols for mine reject soils, enabling their productive utilization. The institute has pioneered soil and water conservation measures specifically designed for various plantation crops under coastal climatic conditions. Research breakthroughs in plantation crop-based land-use systems and coconut-rice integrated farming systems have provided viable models for sustainable agriculture in coastal regions. The institute has made substantial contributions to enhancing productivity in coastal saline soils through development of salt-tolerant rice varieties and innovative soil amelioration techniques. Integrated pest and disease management strategies have been formulated for field crops, plantation crops, and horticultural species, addressing region-specific challenges. Comprehensive technology packages for cultivation of plantation and horticultural crops adapted to coastal ecosystems have been standardized and disseminated to farming communities.

Advances in Animal Sciences Research

Since its inception, the Animal Sciences section of ICAR-CCARI has played a pivotal role in strengthening livestock and poultry systems of the coastal region. The section has conserved and characterized unique indigenous genetic resources such as the Shweta Kapila cattle and the Agonda Goa pig, establishing their productive and adaptive traits under humid–saline environments. A significant technological breakthrough has been the development and patenting of a Novel Boar Semen Extender (NBSE), enabling prolonged preservation of semen at ambient coastal conditions, which has widened the scope of artificial insemination in pig farming. Research has also focused on reproductive disorders such as infertility, repeat breeding, and hormonal imbalances in cattle, goats, and pigs, providing practical solutions for coastal farmers. In addition, protocols for semen processing, breeding soundness evaluation, and conservation of livestock germplasm have been standardized, contributing to breed improvement and genetic security.

Equally important has been the institute's work in animal health and livelihood resilience. The section has established systems for animal disease monitoring and surveillance in coastal regions, helping in early detection and control of endemic and emerging livestock diseases. This complements interventions in feeding, housing, and climate-resilient management tailored to humid coastal zones. Beyond conventional approaches, CCARI has documented and validated ethno-veterinary medicine practices among tribal and coastal communities, integrating traditional wisdom with scientific evidence for low-cost animal healthcare. The division has also promoted backyard poultry technologies, value-added processing of animal products, and farmer training in scientific animal husbandry. Through these integrated contributions, the Animal Sciences section has significantly enhanced the productivity, sustainability, and climate resilience of livestock-based systems in India's coastal belt.

Pioneering Work in Fisheries Science

The fisheries science division has achieved remarkable success in developing integrated farming systems combining fish culture with rice, poultry, and duck production. Major innovations include commercialization of low-cost ornamental fish feed formulations and establishment of protocols for freshwater ornamental fish culture. The institute has successfully demonstrated mussel, cage and crab farming techniques in brackish water regions of Goa, opening new avenues for coastal aquaculture.

Advanced technological interventions include remote sensing-based Potential Fishing Zone (PFZ) forecasting with field validations, development of artificial fish habitats to enhance fish productivity, and low-cost capture-based multispecies culture systems. Comprehensive documentation of fish assemblages from estuarine ecosystems, freshwater systems, islands, and artificial habitats has contributed valuable biodiversity data. The institute has conducted appraisals of recreational fisheries potential in Goa and provided scientific demonstrations of sustainable fish harvesting systems, promoting responsible fishing practices while maintaining ecological balance. These multidisciplinary research achievements collectively address the complex challenges of coastal agriculture while promoting sustainable resource utilization and improving livelihoods of coastal communities.

Research Initiatives in Fisheries

The Fisheries section of the institute has developed a few integrated fish farming technologies. Moreover, the institute has come up with cost-effective feeds for ornamental fish culture using locally available ingredients mainly the by-products of agro-industries. The institute is also propagating the culture techniques of producing live fish feeds, which is important at the hatchery level rearing of fish spawn and fry. The activities under NABARD funded ornamental fisheries projectand theICAR Seed Project has helped in the production of quality ornamental fish seed. About 700 people were trained on various aspects of ornamental fish breeding and rearing, low-cost feed formulation, disease and health management, water quality and also fabrication of aquarium tanks. Five of the trained farmer groups have already initiated to produce ornamental fishes on a commercial scale.The institute is also initiated the development of a database on the fisheries resource of Goa including marine, freshwater and brackish water resources, their trends and future scope for development. Moreover, the technology options for the fisheries enhancement in Goa will be also provided under this database.

Low-Cost Capture Based Multispecies Culture System for Coastal Waters of Goa

A continuous stocking and harvesting system including finfishes like red snapper *(L. argentimaculatus)* and pearlspot *(Etroplus suratensis)* were cultured in combination with a shellfish species, Green mussel, *Perna viridis for* a period of eight months. These types of culture techniques are suitable for the coastal khazan areas called Manas (sluice gate operating areas). Finfish seeds obtained as a by-catch during the fishing operations were separately stocked in nylon hapas (2m x 1.5m x 2 m) positioned using bamboo poles. Mussel seeds collected from the wild were stocked in cotton mosquito net bags. The BC ratio from the culture was more than 2.5 and thus, this system can function as a source of alternate livelihood for youth.

Integrated Fish Farming System Model for Low Land Situations

An integrated farming system model with enterprises rice (Vytilla)-fish (Rohu, *Labeo rohita*), poultry (Gramapriya), cow pea (Goa Cowpea-3), fodder (IGFRI-3) and cucurbitaceous vegetables were tested under the low land situation of Goa. The total area of the system was 0.07 ha (Rice - 0.06 ha, fish – a trench - 40 m2 and 1 m deep and rest of the area for fodder and vegetables). The benefit cost ratio of the model was 2.37. The order of contribution of the enterprises to net profit was – fish (32%) > poultry (23%) > rice (20%) > fodder (16%) > cowpea (5%) > cucurbits (4%).

Livestock–Fish–Horticulture Based Integrated Farming System (IFS)

A novel Livestock–Fish–Horticulture Based Integrated Farming System (IFS) was developed by ICAR–CCARI, Goa, to enhance the profitability, sustainability, and livelihood security of small and marginal farmers in the coastal regions of Goa and the adjoining west coast. The model integrates aquaculture, livestock, and horticulture components within a single farming system, promoting efficient recycling of organic waste, nutrient utilization, and resource conservation. Compared to conventional monocropping, the IFS demonstrated remarkable economic and environmental advantages, recording a net profit of ₹46.4 lakhs and a Benefit–Cost ratio of 2.6, nearly double that of the traditional practice (1.5). The system significantly reduced income risk through diversification, ensured year-round production, and improved resource-use efficiency with a net energy gain of 5,68,955 MJ and an energy profitability index of 5.63. Furthermore, the IFS saved approximately 2000 m³ of water annually and achieved a 230% increase in overall yield through synergistic linkages among system components.

Reclamation of Salt-Affected Khazan Soils Through Aquaculture Interventions

Khazan lands of Goa, covering 18,921 hectares along estuarine stretches, are unique agro-aqua-forestry landscapes traditionally managed as paddy fields and salt pans. These systems face multiple challenges, including acidic soil pH, excessive salinity from saltwater intrusion, fallowing of coastal saline soils, abandonment of agriculture, rice monocropping, and poor productivity. Standalone paddy cultivation is no longer economically viable, necessitating the integration of aquaculture to restore productivity, enhance fish diversification, and improve rural livelihoods. Four ponds (150–360 m²) in Goa's Khazan lands were excavated and prepared to enhance aquaculture productivity and reclaim salt-affected soils. Pond preparation included weed removal, elimination of forage fishes and predators, and liming. Post-stocking management involved liming, fertilization with urea, single super phosphate, phosphate-rich organic manure, biochar, probiotics and other organic and inorganic amendments to improve water and soil quality. Polyculture stocking included *Catla catla, Labeo rohita*, *Etroplus suratensis*, and Gift Tilapia at 0.5 fingerlings/m². Water pH increased by 97%, soil salinity reduced by 82% and plankton density increased by 53.16%, and fish growth was satisfactory. One pond suffered complete mortality due to flooding, but overall system resilience was observed. These interventions reclaimed saline soils, enhanced fish productivity, enabled crop diversification on bunds, and strengthened rural livelihoods in Khazan ecosystems.

Floating Duck-Cum-Fish Cage Unit

An innovative floating duck-fish cage system was designed and implemented to promote nutrient recycling and sustainable aquaculture. The 16 m² platform accommodates 800–1000 juvenile fish (5–8 cm) and 15 ducks, constructed using metal, fibre, plastic, and aluminium, with plastic barrels for buoyancy. Duck droppings act as natural fertilizer, enhancing plankton growth, reducing feed requirements, and boosting fish productivity. The mobile structure can be relocated within or between ponds as needed. Around 250kg of tilapia fish and 60 kg of ducks were harvested using this model. The model was economically feasible, with an initial investment of ₹2,65,000 and gross and net returns of ₹1,40,000 and ₹75,000 per unit, respectively, in the first cycle.

Novel Crab Farming Methodology for the Coastal Region

A climate-resilient crab farming system was developed using HDPE barrels to keep crabs 0.8–1.2 m under water, reducing water temperature by 1–1.5 °C and minimizing heat stress. Perforated barrels (50–80 L) were designed with provisions for water exchange, feeding, and waste removal. The system can generate an additional monthly income of ₹800–1,000 per barrel for fishermen and farmers.

Portable Bamboo Aquarium for Ornamental Fish Rearing

bamboo base and top to develop a portable ornamental fish rearing system. The base is illuminated with LED lights powered by rechargeable batteries, and the top has provisions for feeding and oxygen administration. The design is compact, user-friendly, ecofriendly, and suitable as a livelihood option for women SHG members. With a production cost of ₹1,000 and a sale price of ₹2,000, it offers a viable start-up opportunity.

Promotion of Mussel Culture

The mussel culture was demonstrated at Kerala, Karnataka and Maharashtra, optimizing rack design, rope dimensions, spacing, seed size, seeding density, and culture duration for enhanced productivity. The system used a 5 m × 5 m bamboo rack (bamboo poles of 15–20 cm diameter) supporting 100 nylon/coir ropes (2.8 cm dia) spaced at 25 cm intervals. Each rope was seeded with 1.0-1.2 kg of mussel spat (22–35 mm) enclosed in stitched cotton bags (2.5 mm thick, 1 m × 0.35 m). A net income of ₹27,900 per rack with a Benefit-Cost Ratio of 2.32, was generated using this methodology.

Promotion of Ornamental Fish Culture Through Training and Demonstration Programs in Goa

Five training programs on ornamental fish culture were conducted, benefiting 100 trainees across Goa with hands-on skills in tank fabrication, breeding, disease management, and entrepreneurship. Five demonstration units were established at Diwar Island, Assonora, Cumbarjua, ICAR facility, and Parra, equipped with tanks, filtration systems, and diverse fish species. Two extension folders were published on freshwater ornamental fishes and sustainable entrepreneurship practices. Around 40,000 small indigenous fish seeds were produced through pond breeding for conservation and aquaculture experiments. These initiatives created sustainable livelihood opportunities for 100 community members, including women and ST fishermen/farmers in different regions.The captive breeding of several key SIF species, including *Haludaria pradhani, Pethia setnai, Rasbora dandia, Systomus sarana,* and *Puntius vittatus* is carried out at the Insitute. These species were reared in natural pond ecosystems to establish a sustainable stock for conservation efforts. Additionally, efforts to enhance seed production through broodstock development were implemented, which are now being maintained in live gene banks at ICAR-CCARI

Comparative Life Cycle Assessment of Whiteleg Shrimp *(Penaeus vannamei)* Farming Along the West Coast of India

A life cycle assessment was conducted on shrimp farms along India's west coast to compare intensive HDPE-lined and semi-intensive earthen pond systems. Using ISO-compliant cradle-to-farm-gate analysis, HDPE ponds showed higher emissions (369.04 kg CO_2 eq/ton) and 28.14% more terrestrial acidification, while earthen ponds had 38.09% higher marine eutrophication. Seed production, electricity use, and feed inputs were identified as key environmental impact drivers. Intensive systems provided higher yields but incurred greater environmental costs, highlighting trade-offs in shrimp farming practices.

Conservation and Management of Fish Diversity of Ramsar Site: Nanda Lake, Goa

Exploratory studies were conducted at Nanda Lake, a Ramsar site of international importance in Goa, to assess fish biodiversity and ecosystem health. A total of 17 fish species were documented, including *Pethiasetnai* and *Haludaria pradhani,* both listed as threatened by the IUCN Red List. Declines in fish diversity indicated habitat degradation and the need for conservation measures. ICAR-CCARI initiated conservation action plans emphasizing habitat restoration, community participation, and sustainable management. Future plans include broodstock collection and captive breeding of threatened species in collaboration with local and governmental stakeholders.

Assessment of Freshwater Fish Diversity in Goa's Riverine Ecosystems

The exploration for fish fauna in Goa's riverine ecosystems-Mandovi, Zuari, Terekhol, and Chapora. yielded a total of 84 fish species were documented, belonging to 59 genera, 26 families, and 12 orders. The family Cyprinidae was the most dominant group with 28 species, followed by Nemacheilidae and Oxudercidae with six species each. Among the river systems surveyed, the Mandovi River exhibited the highest diversity, with a Shannon diversity index (H') ranging from 2.38 to 2.41 and species counts between 36 and 38. Eight species recorded during the survey are listed as Threatened under the IUCN Red List, including *Haludaria pradhani* (Endangered), *Pethia setnai* (Vulnerable), and *Hypselobarbus curmuca* (Endangered) and *Carinotetraodon imitator* (Vulnerable). Invasive alien species such as *Oreochromis mossambicus* and *Clarias gariepinus* were also recorded, indicating potential ecological threats to native fish assemblages.

Fish Biodiversity of Protected Forest Areas of Goa

Under a project funded by the Forest Department, titled "Fish Biodiversity Survey, Inventory and Documentation from Streams and Rivers in Notified Government Forest and Protected Areas of Goa for Conservation and Management", surveys are being conducted across six key sanctuaries of Goa—Bhagwan Mahavir Wildlife Sanctuary, Mhadei Wildlife Sanctuary, Netravali Wildlife Sanctuary, Cotigao Wildlife Sanctuary, Bondla Wildlife Sanctuary, and Dr. Salim Ali Bird Sanctuary. Documentation work was initiated on stream wise inventory, documenting indigenous and endemic fish species, their distribution patterns, relative abundance, and habitat preferences. This project aims at assessing the conservation status of lesser-known native species, many of which are restricted to forested aquatic ecosystems. The study also aimed for anthropogenic pressures and habitat degradation as key threats and culminated in science-based recommendations for the long-term conservation and sustainable management of Goa's freshwater fish biodiversity within these ecologically sensitive zones. Particular focus has been placed on the conservation status of rare and threatened taxa, habitat characterization, and identifying anthropogenic pressures. The project directly contributes to SDG 15 (Life on Land) and SDG 6 (Clean Water and Sanitation) by enhancing conservation planning for freshwater ecosystems within Goa's critical forest zones.

Building Capacity for Climate Change Adaptation in Smallholder Fish Farming

A comprehensive climate change adaptation project was successfully designed and launched, targeting smallholder fish farmers across 13 states, with an objective of training and capacity building of over 6,000 smallholder fish farmers, with a special emphasis on empowering 1,200 women farmers in climate-resilient aquaculture practices.. As part of the initiative, a climate risk assessment study was conducted for the Phase I states—Maharashtra, Karnataka and Kerala—integrating scientific climate data analysis with extensive farmer consultations. Customized training modules were developed to address climate-resilient fish farming, aquaculture-based livelihood diversification, financial management, and market linkages, tailored specifically to the needs of women and marginal fish farmers. Baseline survey tools and stakeholder mapping frameworks were prepared and deployed to inform strategic implementation. Field recruitment was facilitated, along with stakeholder consultations and site visits for need assessment and farmer identification in the three Phase I states. The project also oversaw the development of structured training content covering key areas such as biosecurity, climate-resilient species selection, budgeting, credit access, savings behavior, marketing and supply chain awareness, and the promotion of both online and offline extension systems to support continuous learning. Project activities were aligned with national fisheries development schemes like PMMSY, DAY-NRLM, and FIDF to ensure policy coherence and effective implementation. Additionally, a climate risk assessment study was conducted to evaluate the vulnerability of aquaculture systems under changing climatic conditions and to design suitable adaptation strategies. Local institutions such as Krishi Vigyan Kendras (KVKs), Self-Help Groups (SHGs), and State Fisheries Departments were actively engaged for training collaboration and implementation support.

Agro-Eco Tourism

Agro-eco-tourism is an applied part of agriculture research in which, there is synergistic combination of agriculture is emphasized along with the tourism opportunities. This concept is recently developed to make the farming profitable and a source of income for the agricultural farmers. A model unit of agro-eco-tourism with agriculture, fishery and animal components at the institute premises. There were constraints in the spatial aspects and blending of the components with the holistic agro-eco-tourism concept. Nevertheless, remarkable progress was made in the establishment of the components at the Agro-eco-tourism centre of the institute. The institute established various components at the Agro-eco-tourism centre of the Institute.

The ICAR-CCARI has made significant contributions to the promotion of agro-ecotourism in the coastal region, positioning it as a viable avenue for diversification of farm income, rural employment generation, and conservation of natural resources. The institute spearheaded the preparation of the State Policy on Promotion and Regulation of Agro-Eco-Tourism in Goa, which was formally released by the Hon'ble Chief Minister and supported by a special budgetary provision in the State Assembly. Demonstration models integrating coastal farming systems with tourism elements such as spice gardens, integrated farming system units, heritage rice landscapes, and island-based eco-trails have been established for farmer training and visitor engagement. Further, the institute has conducted capacity-building programs for farmers, FPOs, women SHGs, and youth on agro-tourism entrepreneurship, branding, and value addition, while fostering collaborations with GTDC, NABARD, and other stakeholders. These initiatives have strengthened the interface between agriculture, culture, and tourism, thereby enhancing farmer incomes, preserving biodiversity, and creating climate-resilient livelihood options in the coastal region of India.

The institute is developing a comprehensive agro-ecotourism unit at Chorao Island, one of Goa's ecologically significant estuarine islands known for its rich mangrove ecosystems and biodiversity. This satellite facility is being designed as an integrated demonstration center showcasing sustainable coastal agriculture practices, traditional farming systems, mangrove conservation, and estuarine fisheries management. The Chorao unit will feature live demonstrations of coastal farming techniques, traditional fishing methods, crab farming, and educational trails highlighting the interconnections between agriculture, aquaculture, and mangrove ecosystems. By strategically positioning this facility on an island ecosystem, ICAR-CCARI aims to create an immersive learning experience for farmers, students, tourists, and policymakers while promoting community-based conservation and sustainable livelihood models. The unit will also serve as a field laboratory for research on island agriculture, climate resilience, and ecosystem-based adaptation strategies relevant to coastal and island communities across India.

Coastal Agriculture Information System

ICAR-CCARI has developed a comprehensive digital Coastal Information System to integrate real-time data on coastal agriculture, fisheries resources, weather patterns, market intelligence, and best management practices. This web-based platform is serving as a centralized knowledge repository and decision-support tool for farmers, fishermen, researchers, extension workers, and policymakers across India's coastal regions. By leveraging Information and Communication Technology (ICT), the system aims to bridge the information gap between research institutions and end-users, enabling timely access to scientific knowledge and fostering data-driven decision-making. The platform will also facilitate two-way communication, allowing farmers and fishermen to report field observations, seek expert guidance, and share traditional knowledge, thereby creating a collaborative ecosystem for sustainable coastal resource management. Integration with mobile applications will ensure last-mile connectivity, particularly benefiting remote coastal communities.

Future Thrust

The future thrust should include intensified R & D efforts in soil and water management, biodiversity and conservation of crop resources, precision farming, integrated farming systems, Genetic management and production strategies for livestock, management of coastal fisheries resources and integrated multi-species fish farming practices and long range forecasting and forewarning against the possible floods, cyclones and tidal waves using space technology, radar detection and protection, remote sensed data, computer technology, radio, cell phones etc,. improvement of market intelligence and guarantee facilities in the light of the expanded export opportunities– agriculture, aquaculture, horticulture, sericulture, dairy and poultry products, support for crop, livestock, and infrastructure, insurance, reclamation of salt affected soils, creation of wind barriers, scientific exploitation of the biodiversity, mangroves, wind and water energy etc. prevention of human induced (anthropogenic) factors in the ecological degradation, improvement and extension of technologies, improving irrigation and drainage systems and their management, improving post-harvest infrastructure and better exploitation of river sources.

The institute has identified research schemes which benefit the coastal agriculture system. As a part of widening the scope for the entire coastal zone of the country, it will focus towards efficient cropping, culture, production, marketing and management system to enhance the income from agriculture, animal husbandry and fisheries. A framework of efficient stakeholders will pave the way towards key future developments in this sector.

A Roadmap for Coastal Sustainability

ICAR-CCARI's comprehensive research portfolio demonstrates that sustainable coastal agriculture is achievable through integrated, science-based approaches. Key achievements include:

- Development of climate resilient farming systems with demonstrated economic viability
- Conservation of endangered aquatic biodiversity through captive breeding
- Innovation in low-cost, eco-friendly multi-species aquaculture technologies
- Developing a framework for assessment of fisheries and fish-based ecosystem services of estuaries
- Capacity building for thousands of farmers, with special emphasis on women and marginalized communities
- Creation of knowledge platforms linking research, extension, and policy

The institute's future focus emphasizes:

- Intensified soil and water management research
- Precision farming and genetic resource conservation

- Long-range climate forecasting and disaster preparedness
- Market intelligence and export facilitation
- Scientific exploitation of biodiversity, mangroves, and renewable energy
- Improved post-harvest infrastructure and value chains

As coastal populations face intensifying pressures from climate change, resource depletion, and development pressures, ICAR-CCARI's model of integrated coastal agriculture offers a blueprint for balancing productivity with ecological sustainability. Through continued collaboration with farming communities, government agencies, and research institutions, the institute aims to secure food security, livelihood resilience, and environmental conservation for India's coastal regions.

Recent Advances and Innovations in Brackishwater Aquaculture for Resilient and Sustainable Development

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As the demand for seafood increases globally, aquaculture plays a multifaceted role in supporting food security, economic development and environmental sustainability. It is the fastest growing food producing sector creating livelihood for the coastal communities. According to FAO's 2024 State of World Fisheries and Aquaculture (SOFIA) report, the total global production reached a value of USD 313 billion, reflecting the sectors expansion particularly in Asian countries and its output is expected to reach 205 million tonnes by the year 2032. India ranks as the third largest contributor to global aquaculture accounting for 8% of the total production. In 2024, India recorded 13.9 million tonnes of inland and aquaculture production, 4.5 million metric tonnes of marine fisheries production and 1.22 million metric tonnes of Brackishwater aquaculture production. This represents a growth from 12.1 million tonnes in 2022 and is projected to double to 28.8 million tonnes by 2033, fuelled by a 7.5 % compound annual growth rate. Among various forms of aquaculture, brackishwater farming holds significant potential for enhancing seafood supply especially through export. As of the financial year 2023-24, India's seafood export reached 1.78 million metric tonnes valued at 7.38 billion USD. Shrimp exports were a significant contributor generating a revenue of 4.88 billion USD. (MPEDA 2024)

Sustainable coastal aquaculture not only boosts seafood production but also provides an alternate to wild capture fisheries thereby preserving marine biodiversity and maintain ecological balance of marine ecosystem. Among various brackishwater species, shrimp farming has emerged as a major contributor of India's aquaculture growth. This shift towards sustainable practices is evident in the growth of shrimp farming across the country. Farmed shrimp, especially Penaeus vannamei dominates the Indian aquaculture space, with India holding a leading position in global shrimp exports. Recognizing the potential the Government of India has launched targeted initiatives to boost sustainable growth of this sector.

Several states play a major role in driving the growth of the country's fisheries production. Andhra Pradesh is the largest shrimp producing state (three district contribute 75% of the state production- Krishna, west Godavari and east Godavari), followed by West Bengal, Gujarat and Odisha. Brackishwater environments support a variety of euryhaline fish and shellfish species that are adapted to fluctuating salinity levels. The sector utilizes vast stretches of India's 12.4 lakh hectares of brackish water resources, much of which was previously unproductive land, and has become a significant contributor to the livelihoods of coastal communities.

Giant tiger prawn (*Penaeus monodon*) and, more recently, the exotic white leg shrimp (*Penaeus vannamei*) playing a crucial role due to availability of genetically improved variety with fast growth rates, SPF status, and high market value, making shrimp the dominant product of the sector. In addition to shrimp, other cultivated species include finfish like seabass, milkfish and mullets, as well as bivalves and seaweeds, though their production remains relatively low compared to shrimp.

Traditional farming systems rely on tidal flows to bring in natural seed and nutrients, with minimal external inputs, while more modern approaches—such as extensive, semi-intensive, intensive and super-intensive systems—incorporate higher stocking densities, supplemental feeding, and improved management practices to boost productivity.

ICAR- Central Institute of Brackishwater Aquaculture (CIBA) centres on advancing scientific research and technological innovations to support the sector. The institute's research focuses on diversified systems such as organic farming, modified extensive to intensive farming, biofloc-based farming technology, recirculating aquaculture systems (RAS) and two/three phase farming with nursery integration, and recently developed Super-intensive precision and natural shrimp farming incorporating automation to enhance farm management for smart aquaculture. ICAR-CIBA, research examines the socioeconomic impact of this industry, focusing on empowering small and marginal farmers, improving market access, and creating sustainable livelihoods.

Further, ICAR-CIBA, focuses on the species diversification, disease management (diagnostic tools for early detection of diseases), socioeconomic impact analysis, developing eco-friendly feed alternative to reduce reliance on fish meal, development of fast-growing breeds for the commercially important finfish and shrimp species by selective breeding programs as well as gene editing techniques to improve traits and further a significant strides in advancing brackishwater aquaculture through innovations like integrated seaweed–shrimp farming, hatchery-based mud crab cultivation. Despite the advancements, Indian brackishwater aquaculture need to address climate change issues developing climate-resilient aquaculture models. To tackle the rising sea levels and salinity fluctuations which can disrupt traditional farming practices.

Challenges and Constraints in Aquaculture Development

The Indian farmers are encountering both technological and infrastructural issues. Many aquaculture farmers lack access to the latest research and best practices which limits productivity and sustainability. Also, poverty and lack of investment in rural areas can limit the capacity of farmers to adopt improved aquaculture techniques. Key technological challenges include the high cost of feed, lack of access to quality seeds, and biological hazards. In terms of infrastructure, challenges consist of difficulties with credit, marketing, pond ownership, limited technical skills, and extension services. Small-scale farmers may struggle to access markets or receive fair prices for their products due to inadequate infrastructure and competition. Additionally, the farmers encounter challenges on environmental degradation, including water pollution, habitat loss, and mangrove restoration for long-term sustainability, especially in coastal and brackishwater zones. Climate change impacts, such as erratic rainfall, rising sea levels, and temperature fluctuations, further disrupt farming cycles and increase vulnerability to disease outbreaks. Alongside, Regulatory gaps and weak enforcement, social barriers, market-related issues pose risk. Tackling these challenges necessitates a collaborative approach that includes government backing, science-based farming practices, active community participation, and investment in technology and education.

Sustainable Aquaculture: A pathway to Blue Economy Development

The rapid expansion of aquaculture, driven by both domestic and international markets, has raised concerns regarding environmental degradation, overfishing of wild stocks, and socio-economic challenges for local communities. These issues underscore the need for sustainable practices that balance production with ecological integrity. This gives considerable scope for genetics/biotechnological and other technological interventions. Hence, the concept of delivering high production with a sustainable approach through evolving eco-friendly technologies started getting momentum worldwide. The low input based on traditional integrated agriculture-aquaculture systems such as paddy cum fish culture, live-stock fish culture, and polyculture is sustainable traditional farming models. Antimicrobial resistance from excessive antibiotic use in aquaculture is a growing concern, highlighting the need for regulation and probiotic-based alternatives. Water scarcity further demands efficient systems like RAS and biofloc to conserve resources. Innovations such as aquaponics, IMTA, biofloc technology and renewable energy solutions are being explored to reduce environmental impact. Climate-smart approaches like salinity-tolerant species and early warning systems help adapt to shifting conditions, while digital tools and training programs are crucial to equip farmers with practical knowledge. Diversification of species and production systems and adopting sustainable intensive systems and Artificial intelligence (A.I.) based smart systems are the need of the hour for doubling production and income.

Technological Advances for Transforming Sustainable and Advanced Aquaculture

Several sustainable innovative practices in aquaculture production systems are being promoted to address the challenges faced by the sector. These include:

A. Aquaculture Production Systems and Husbandry:

Asian Seabass Hatchery Facility and Demonstration of Three-Tier Farming Practices

Seabass is considered as one of the most sought-after food fishes in India, commanding a farm-gate price of ₹400 to ₹500 per kilogram. It is a euryhaline species, making it suitable for culture in a wide range of salinities (0 to 35 ppt) both in the pond and open water cage culture systems.

ICAR - Central Institute of Brackishwater Aquaculture has been at the forefront of developing and implementing customized farming technologies for high-value fish species, particularly the Asian seabass (*Lates calcarifer*). These technologies encompass the entire value chain, from seed production to grow-out, making them highly suitable for adoption by coastal communities. CIBA team can demonstrate and implement seabass hatchery and farming through systematic demonstration and support for local entrepreneurs and farmers as income generation activity.

Super-Intensive, Precision, and Natural Shrimp Farming System (Corporate Entity/ Entrepreneurship Model/FFPO)

ICAR-CIBA has developed an indigenous "Super-intensive Precision and Natural Farming System" (SIPNSF) under the PMMSY scheme of the GoI. This integrates the Institute's core technological innovations into a high efficiency, low impact farming model. In a super intensive setup, the stocking density is significantly higher than in traditional aquaculture systems. (to counter low survival; small sizes and biosecurity issues in earthen ponds, a high yield up to 45-50 tons/ha/yr in 90-120 days with survival rates of 86.5%–97.8% and FCRs of 0.97–1.2. . Key features of the model include smart feeding, intelligent aeration, string net biosecurity. In situ natural feed production, minimal water exchange, and low energy consumption making it climate resilient and environmentally sustainable.

Fig1: Aerial view of a complete unit of Super-Intensive, Precision and Natural Shrimp Farming equipped with automation in feeding, aeration and water monitoring with solar panels

Mud Crab Hatchery and Farming Practices

Mud Crab Hatchery and Farming practices play a pivotal role in the brackishwater aquaculture. The Blue Swimmer Crab (*Portunus reticulatus*), an economically important species, was successfully bred and reared in brackishwater conditions for the first time by ICAR-CIBA with 56% survival. Also, ICAR-CIBA has successfully demonstrated seed production of the Scylla olivacea, Scylla serrata to provide crablet and by fostering entrepreneurship and ensuring long-term sustainability. The hatchery reared mud crabs in earthern ponds achieved a production yield of 700 kg per hectare with average body wt of 720 gms and survival of 45%. To address challenge of long rearing period and poor survival of mudcrab a three-tier modular farming system or zero stocking model was developed. The system consists of three months of nursery rearing, followed by four months of pre grow out and three months of growout phase. This model has demonstrated survival rates of 80% and a yield of 1.1 tonnes per hectare during the growout phase highligt its potential.

Seaweed–Shrimp Integrated Farming System

Combines seaweed *Gracilaria* sp. with shrimp farming to create a sustainable and productive aquaculture model. In this system, seaweed absorbs excess nutrients from shrimp ponds, improving water quality. This helps in enhanced shrimp growth with lower risks of diseases, while seaweed biomass provides an additional income without extra output costs. This system promotes resource efficiency, environmental stability and increased profit for farmers.

Fig 2: Harvested seaweed from the seaweed -shrimp farming system

Diversification into Other Penaeid Shrimp Species/ Ornamental Species Especially in Coastal Aquaculture *(P. indicus/ P. monodon, P. japonicus & P. merguinsis*) and fish species like Seabass, Sea bream, Mullets, Milkfish, Pearl spot, etc.,

Adopting Genetically Improved Species Farming

The genetically improved varieties like SPF penaeids (*P. monodon, P. vannamei*), GI Scampi, GIFT, improved Catla/ Rohu are important candidate species for tropical aquaculture due to their fast growth rate, short culture duration, tolerance to water quality variation, disease resistance/tolerance, and easy culture techniques with better adaptability to wide water quality parameters.

Multi-Phase Aquaculture System

Unlike traditional aquaculture methods, which often focus on single species in a single environment, multi-phase systems integrate various stages of aquatic organisms' life cycles and species, optimizing space and resources. In a multi-phase aquaculture system, different stages of fish growth are cultivated in separate but interconnected environments which gives more harvests per year.

Biofloc and Periphyton Based Eco-friendly Farming

By harnessing the power of microbial communities and promoting natural biodiversity, these innovative systems not only enhance productivity but also contribute to a more sustainable and resilient food production system. Bio-floc systems result in increases of 30 to 50% in weight and almost 60-80% in final biomass in shrimp at early post larval stage and 15-20% lower cost of production when compared to conventional clear-water system.

Fig 3: Biofloc facility at Kelambakkam Experimental Station of ICAR- CIBA

Nursery Rearing System (conventional/BFT) for shrimp/fish- The nursery rearing system, whether conventional or utilizing biofloc Technology, is crucial for the successful cultivation of shrimp and fish. While conventional systems provide a foundational approach, BFT offers a more sustainable and resource-efficient alternative. BFT supports high density, biosecurity, maintains the water quality even in the absence of water exchange, utilizes maximum of the nitrogen input added as feed, finally resulting in economically viable system.

Recirculatory Aquaculture System-evaluation & Adoption

RAS are extremely productive intensive farming systems for varied marine species that can run all year, in a range of locations, including proximity to major seafood markets, and are not impacted by seasonality or environmental factors while providing a strong revenue source.

B. Reproduction and Genetic Improvement:

- Genetic improvement of farmed species is very much required in aquaculture as the application of genetic principles to increase production is far more lagging here compared to that of animal and plant science.
- Similarly shrimp genetics improvement program have contributed immensely for the revolution in the sector through adoption of SPR/SPT and SPF lines
- Genome-based technologies in aquaculture research, Selective breeding programme and the production of monosex and sterile populations
- Carp and tilapia culture in Asia is benefiting from genetics research in a number of areas, including genetic sequencing and the development of specific genetic markers. The GIFT project has been instrumental for producing pure-bred lines and the distribution of strains of improved performance to farmers.
- ICAR-CIBA's Genetic Improvement Programme for Indian White Shrimp (Penaeus indicus) is a flagship initiative launched under the Pradhan Mantri Matsya Sampada Yojana (PMMSY) to reduce India's dependence on exotic shrimp species like P. vannamei. Recognized as a national priority under the Make in India mission, the program aims to develop high-performing, disease-resistant indigenous shrimp strains.
- The establishment of the Nuclear Breeding Centre (NBC), is completed and the Genetic Improvement Program of *P. indicus* is now being initiated.

C. Nutritional Advances

Improvements in aquaculture nutrition play a key role in boosting productivity while supporting sustainability and economic growth in the industry. As concerns rise about the environmental footprint and rising costs of traditional feed ingredients, new and creative methods are being explored to make feeds more efficient and eco-friendlier.

- Reducing dependence on fish meal & animal protein and possible enhancement of inclusion rate of plant protein
- Alternate protein sources (BS Fly / Krill meal)
- Precision nutrition and feed systems that meet the needs of the system
- Nutrigenomics approach for better performance
- Usage of SPF live polychaetes as broodstock feed
- Pellet feed is replaced by extruded feed because of its less dust and lesser broken pellets and its more water stability
- Fish Waste Processing technology for producing value-added products from fish processing waste (Entrepreneurship model/FFPO)

D. Disease Diagnostics and Health Management

- Surveillance for existing and emerging diseases of coastal farming
- Control of viral and parasitic diseases, improving disease resistance through genetic selection
- Novel system adoption *i.e. circular* tank model is one of the best solutions to control EHP due to its clean bottom and good water quality, microsporidium kept in control
- Epidemiological studies, functional diets, and Genetic selection acts as prophylactic action and prevent the outbreak of diseases.

E. Pond Automation and IoT

- Usage of IoT for maintenance of water quality parameters in nurseries and growout farms
- AI & IoT application in Feeding & Water quality Management, etc.
- Feeding shrimps using Aqua robots
- Automatic power factor control
- Precision Farming by using drones and robots to observe, measure and respond to spatial and temporal variability to improve production sustainability.

F. Market Research, Credit, Insurance, Start-ups

- Development of domestic marketing
- Fish & Shrimp Processing and packaging of the produce and supply value chain
- Building a sustainable circular economy
- Crop Rotation and scheduling
- Crop insurance Technologies like Super intensive, Circular-tank systems take less initial investment (than lined ponds), Less risk, and more predictable production.

Role of ICAR- CIBA in Technology Dissemination

ICAR-CIBA, is one of the foremost scientific research institutes in brackishwater aquaculture working towards constructing the country's emerging blue economy. ICAR-CIBA has standardized the technological innovations in coastal aquaculture disseminating the technology across the country. Our institute have a close cooperation with state fisheries department and provide support on many fronts like technology dissemination, promoting species diversification, disease surveillance, research, and management of healthy fish/shrimp for better life style.

The institute have established hatcheries for the production of diversified finfish species such as Seabass, Mullet, Milk fish (*Chanos chanos*), Pearl spot (*Etroplus suratensis*), and low value species like *Mystus gulio*. With respect to crustacean culture, the institute has been prioritizing the culture of Indian white shrimp, *P. indicus* and have initiated a selective breeding program in partnership to establish hatchery and propagation of this potential native species as a complementary species to exotic shrimp, *P. vannamei.*

The Institute have also developed methodology for assessing suitable cultivable area for aquaculture through GIS mapping and is currently adopted by different states. State Fisheries departments had shown interest to incorporate this for better planning, resource utilization, Geo tagging and traceability of these high value product. Geospatial mapping of potential zones for the expansion of sustainable aquaculture will be carried out based on environmental characteristics and regulations. Through spatial analysis, data integration, and effective communication, this technology contributes to sustainable practices in the aquaculture sector.

The diagnostic laboratory at ICAR- CIBA is equipped with state-of-the-art diagnostic tools and technologies for the identification of various pathogens, including bacteria, viruses, and parasites. Techniques such as PCR (Polymerase Chain Reaction), histopathology, and serological assays are employed for accurate diagnosis. ICAR-CIBA implements regular disease surveillance programs across different states of aquaculture farms to monitor the health status of aquatic species.

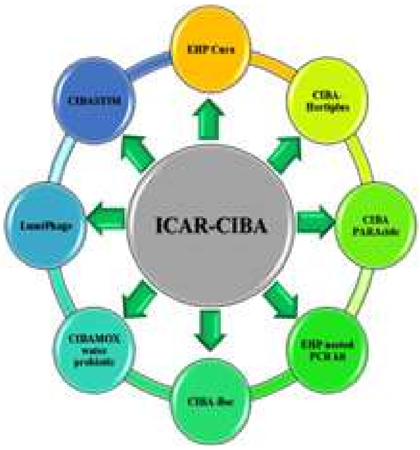

Illustration 1- Products by ICAR-CIBA for enhancing production, improving water quality and mitigating disease occurrence.

ICAR- CIBA has developed a wide range of products aimed at promoting sustainable and ecofriendly aquaculture practices. It includes CIBAMOX (a microbial formulation for controlling the build-up of toxic nitrogenous metabolites in aquauculture ponds), LUMIPHAGE (consortia of bacteriophages having activity against virulent vibrios), CIBA PARACIDE(for treatment of parasitic infestations in food and ornamnetal fishes), EHP nested PCR kit & WSSV diagnostic kit (molecular diagnostic tool for early detection of EHP and WSSV), CIBAFLOC (microbial consortium for floc generation and water qaulity management), EHP cura I (a therapeutic formulation for control and treatment of EHP), CIBASTIM (microbial immunostimulant for shrimp growth, survival and immunity), CIBA-Hortiplus and CIBA Plankton Plus (fish waste converted into nutrient rich organic fertilizer for horticulture crops and aquaculture ponds). These products reflect the instituition's efforts in promoting sustainable and ecofriendly aquaculture practices in India.

Nursery technology and multi-phase farming including biofloc technology and Standard Operating Procedure (SOP) for P. indicus culture, developed and refined by ICAR-CIBA has been adopted by several farmers in coastal aquaculture along the coastal states of India (East & West coast). The institute also developed technology for high-intensive production system with the support of Pradhan Mantri Matsya Sampada Yojana (PMMSY) such as Next Generation Super-Intensive Precision Shrimp Farming Technology, A high-density, circular HDPE tank-based system with integrated wastewater management and energy-efficient operations. It enables up to 120 tonnes of shrimp per hectare annually in three crop cycles, using fewer inputs like feed and energy.

In addition to shrimp farming, ICAR-CIBA has been involved in promoting fish farming across the country, contributing to the diversification of aquaculture practices in the region. The institute has implemented various research and development initiatives focused on the culture of diverse finfish/shellfish species suitable for brackishwater conditions state of art feed mill for brackishwater fish feeds and Aquaculture Spatial Planning (ASP) and providing national guidelines on various aspects from regulations to insurance, credit and market research. Through its comprehensive research, technology transfer, innovative research, capacity building, and sustainability initiatives, the institute contributes significantly to the growth of a resilient aquaculture sector.

Conclusion

The brackishwater sector in India has witnessed remarkable growth over the past decades, and ICAR-CIBA has been at the forefront of this growth. Through its innovative research activities, training programs, and technology dissemination, ICAR-CIBA aims to enhance the productivity and sustainability of aquaculture practices in Brackishwater sector in India. From developing species-specific hatchery and feed technologies to promoting environmentally sustainable farming models, the institute has addressed certain challenges faced by the farmers and stakeholders. Addressing this challenge requires collaboration among governments, stakeholders and consumers. By encouraging circular economy practices, adopting digital and precision farming approaches, and developing resilient production technologies, the institute strives to strengthen food security, build climate resilience, and enhance the livelihoods of coastal communities. With increasing global awareness and demand for sustainably produced seafood, the aquaculture sector holds immense potential to expand responsibly while ensuring the long-term conservation of aquatic ecosystems for future generations.

A Comprehensive Approach towards Aquatic Biodiversity Conservation: The Transformative Initiatives of ICAR - NBFGR

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The conservation of aquatic biodiversity is fundamentally significant as it includes both ecological stability and human well-being. Ecologically, diverse fish and microbial communities are essential for maintaining the health of aquatic habitats, performing critical functions such as nutrient cycling, water purification and regulating food web dynamics in rivers, lakes and oceans. For humankind, aquatic species are an irreplaceable resource, serving as the primary source of protein and livelihood for millions of people globally, which directly supporting the Blue Economy. Furthermore, genetic diversity within fish populations provides the natural resilience needed to cope with climate change, pollution, and disease outbreaks. Protecting the biological wealth is therefore not merely an environmental task, but a strategic imperative to ensure future food security, sustain livelihoods and preserve the ecological integrity of our planet.

India, a nation globally recognized for its incredible biological heritage, possesses an aquatic biodiversity that is equally vast and vulnerable. With over 3900 recorded fish species dwelling in rivers, lakes, reservoirs and marine ecosystems. The sustained health of the country's water bodies is paramount to ecological balance, nutritional security and the livelihoods of millions. The ICAR - National Bureau of Fish Genetic Resources (ICAR - NBFGR), established in 1983 is at the forefront on conservation effort. Its core mandate is the assessment and conservation of fish genetic resources for intellectual property protection, sustainable utilization. Its vision is not merely about preserving species, but about ensuring the resilience and integrity of the entire aquatic ecosystem through a multi - level strategy encompassing cutting- edge science, policy advocacy and community engagement.

The escalating threats of habitat degradation, climate change, water pollution and genetic erosion necessitate a shift from conventional fisheries management to an ecosystem-based approach. ICAR-NBFGR has embraced this paradigm, implementing a portfolio of transformative initiatives that span from the microscopic world of DNA barcoding to large-scale river ranching programs. The institute acts as the central hub for aquatic genetic resource management in India, steering the nation's efforts to safeguard its invaluable aquatic heritage for future generations. The foundation of all successful conservation efforts is comprehensive knowledge and proper preservation. The ICAR - NBFGR has excelled in establishing a robust knowledge infrastructure and advanced ex-situ conservation facilities. The exploration, documentation and preservation of genomic resources of aquatic life is the institutional backbone for India's aquatic biodiversity conservation. The rigorous field work has been vital for taxonomic validation, stock identification and has led to the discovery of over sixty new fish species in the two decades, significantly contributing to the enrichment of the biodiversity catalogue of our nation.

Cataloguing of Genetic Resources (Ex-situ Conservation)

A comprehensive program for DNA barcoding on marine and freshwater fishes of India is underway. This technique uses a short genetic sequence to identify species, providing a powerful tool for monitoring illegal trade and resolving taxonomic ambiguities. The institute has generated molecular markers for numerous commercially important species and studied the population genetic structure of over 26 finfish and shellfish species to guide stock-specific conservation and ranching programs.

ICAR-NBFGR hosts several critical online databases including Fish barcode Information System, Fish Karyome and Fish and shellfish Microsatellite Database. This digital infrastructure makes data accessible to researchers globally. The Bureau has also established the National Fish Museum and Repository (authorized by the National Biodiversity Authority, Govt. of India), which maintain voucher specimens, tissue samples, microbial repository and a cell line repository including over 85 cell lines accessions for long term genetic preservation and research.

As a safeguard against biodiversity loss, NBFGR has developed and refined ex-situ gene banking techniques of cryopreservation protocols. The institute has successfully developed protocols for the sperm cryopreservation of 30 fish species. This is a crucial initiative for conserving the endangered and other species, as it secures the genetic material for future breeding programs and rehabilitation of wild species. The live fish germplasm resource centre further maintains live broodstock of threatened and endangered species, acting as a dynamic gene bank and a breeding facility for conservation.

Ranching Programs and Habitat Restoration (In-situ Conservation)

Onsite or in-situ conservation is essential for protecting within their natural habitats, directly linking biodiversity with ecosystem health. The efforts of NBFGR in this area involves practical interventions, policy initiatives and a focus on threatened aquatic hotspots.

In the western ghats, a global biodiversity hotspot, NBFGR has developed captive propagation technology for species with significant conservation value. Notable initiatives including ranching of the newly described freshwater fish, Horabagrus obscurus in Chalakudy river (Kerala). Further, restocking the seeds of endemic fishes like Yellow catfish, *Horabagrus brachysoma* and Malabar labeo, *Labeo dussumieri* in the reservoirs of Kerala is also succeeded. These initiatives are designed to not only increase fish populations, but also support the fragile aquatic ecosystems of the region.

The Mahaseer, often referred as King of Indian rivers is a critically endangered riverine fish, whose conservation is a flagship initiative of NBFGR. The said strategy of the institute includes captive breeding protocols for various mahseer species. These scientific breakthroughs allow for the large-scale production of genetically robust seed stock in controlled environments. The institute also standardized the first milt cryopreservation protocol for *Tor tor*, creating a vital gene bank to protect the species for long-term genetic viability. This combined approach of captive propagation and genetic preservation directly supports other activities such as ranching programs, enabling the systematic stocking of fingerlings back into their natural habitat to revive wild populations and strengthen their depleted genetic diversity.

Ecosystem Health Management

The Bureau has a strong focus on aquatic animal health. The institute is instrumental in evaluating the risk posed by indigenous and exotic germplasm, contributing to the formulation of policy documents like the National Strategic Plan on Aquatic Exotics and Quarantine. This is vital for preventing the introduction of invasive species and pathogens that can decimate native biodiversity. Beside these the activities of National Surveillance Programme for Aquatic Animal Diseases (NSPAAD), developing diagnostic capabilities for OIE-listed pathogens and establishing a National Repository of Fish Cell Lines to aid in disease diagnosis and the evaluation of immunomodulators, thereby protecting both wild and farmed fish populations.

Policy Advocacy and State Fish Concept

To mainstream conservation into state-level policy, the ICAR-NBFGR promoted a concept of declaring 'State Fish'. This strategic move has led to the declaration of 18 species as state fish by 22 states, providing a policy-backed conservation status that mobilizes state resources for the protection of a flagship aquatic species and its associated habitat. This advocacy bridged the gap between scientific recommendations and governmental actions. This mobilization of state level policy for a species inherently mobilizes broader protection efforts for its associated habitat, connecting between research driven conservation needs and tangible governmental commitment.

Integrating Livelihood and Community Engagement

Conservation must be a socio-economic imperative. ICAR-NBFGR has successfully linked biodiversity conservation with livelihood security, empowering local communities, particularly in ecologically sensitive regions. In collaboration with the Mangrove Foundation, NBFGR established a facility for marine ornamental fishes in Airoli, Mumbai. This project successfully developed captive propagation technology for 10 clownfish species and upscaled the production. This involved training given to hundreds of beneficiaries from coastal villages, establishing cluster-mode rearing units and distributing seeds. This directly promotes biodiversity conservation by reducing pressure on wild ornamental fish populations, besides an additional livelihood to the coastal community. As a research outcome of this project, a designer clown was developed by NBFGR, which is the crossbred of Amphiprion percula and A. ocellaris.

To uplift the livelihood in Lakshadweep, Germplasm Resource Centre in Agatti Island, Lakshadweep, NBFGR established community aquaculture units, primarily involving local women. By providing training and inputs for rearing captive-bred marine ornamentals (such as clownfish and shrimps), the project has created a sustainable income source for island population, thus, aligning conservation with the Sustainable Development Goals (SDGs). This model is a prime example of achieving conservation through community participation.

Another major initiative by the ICAR-NBFGR is the engagement with Deep Ocean Mission. It is a prestigious program launched by the Govt. of India for the exploration of our Ocean realms. The institute's involvement in this program represents a critical extension of its conservation mandate into India's vast marine frontiers. The major objective of this project is to exploration of deep-sea ichthyo-faunal resources, the generation of molecular signatures, and the development of cell lines of deep-sea fishes. This work provides the initial taxonomic validation and baseline data crucial for underexploited populations, assessing the impact of deep-sea resource exploitation, and ultimately formulating scientifically sound conservation guidelines for India's largely unknown deep-sea biodiversity.

The journey of the ICAR-National Bureau of Fish Genetic Resources is a testament to the power of applied science in biodiversity conservation. By effectively executing its mandate, 'exploration, characterization, and cataloguing' of genetic resources to developing ex-situ cryopreservation technologies and implementing in-situ river ranching programs. In this milieu, the ICAR-NBFGR has solidified its position in aquatic genetic resource management. It uses genetic resources to define management units, employs captive breeding and gene banking to secure endangered species, and utilizes community aquaculture to create economic incentives for conservation. As India progresses toward its vision of Viksit Bharat, the ICAR-NBFGR's ongoing commitment to exploring new frontiers, such as whole-genome sequencing and developing climate-resilient aquaculture species etc. The initiatives taken by ICAR-NBFGR not only safeguard the diverse fish genetic resources, but also ensure the integrity of the aquatic ecosystems that provide vital services to the nation, ensuring food security, environmental health, and sustainable livelihoods for generations to come. NBFGR's work is a vital blueprint for how scientific institutions can lead the charge in translating conservation ethics into tangible ecological and socio-economic outcomes.

CMFRI's Public Facing Transparency R&D: A Saga Enshrining Marine Biology for Industry and Exploration

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Fish is a vital part of India, not just in cuisine but also in cultural traditions. As the fisheries of the country grew from small-scale to large-scale over the last several decades, research on India's fisheries has also grown parallelly, encompassing almost all aspects of fish and fisheries. ICAR- Central Marine Fisheries Research Institute (ICAR-CMFRI) has been an integral part of this growth in fisheries research in India. From its establishment on 03 February 1974, the Institute has expanded its research focus from marine biology to include resource management, mariculture, climate change, socio-economics and biotechnology. Today we are the premier marine fisheries research institute in the country and a leader in the south Asian region, contributing to sustainable marine fisheries of India through its research output.

How we Achieved Research Milestones Addressing Challenges in Marine Biology?

In terms of research output ICAR-CMFRI can lay claim to many research publications and initiatives which have been instrumental in improving the marine fisheries sector of the country in terms of sustainability. A few of the outputs are highlighted:

- Marine Fisheries Census 2025 – ICAR-CMFRI conducted the first comprehensive nationwide Marine Fisheries Census (MFC) in 1980, followed in 2005, 2010 and 2016. In 2025, ICAR-CMFRI is carrying out the 5th MFC, funded by the Dept. of Fisheries, Govt. of India. The MFC will cover 9 maritime states and 4 Union Territories of India and will be a fully digital episode this time. The MFCs have been instrumental is providing ground-level information on fishermen families and their socio-techno details, which formed key inputs in policy making for the marine fisheries sector of the country.
- Comprehensive Marine Fisheries Database – ICAR-CMFRI is the custodian of the National Marine Fisheries Data Centre (NMFDC) which is an extensive database of nearly 1200 species, with respect to their landings and fishing effort expended towards the landings, across all maritime states and Union Territories of India. This database has been a critical input for stock assessments and annual marine fishing landings reports of the country. A recent major milestone was the release of a revised species codebook, offering a systematic phylogenetic classification for over 2,800 species across multiple taxa.
- Marine Fish Stock Status of India - ICAR-CMFRI is at the forefront of marine fish stock assessment in India providing a bird's eye-view of the status of marine stocks in Indian seas. Though conducted periodically, the recent

most comprehensive stock assessment was brought out in 2022 titled "Marine Fish Stock Status of India 2022" covering the assessments on 135 commercially important marine fish stocks. The results indicated that 91.1% of the assessed stocks were in a healthy state and that Indian marine fishery stocks are sustainable. The MFSS reports are planned to be released periodically based on regular stock assessments of major marine fish stocks in India, which will enhance science-based management of marine fisheries in the country.

- Marine Mammal Assessment - In 2025, the Indian seafood export got a major boost when the USA approved seafood exports from India as compliant with its Marine Mammal Protection Act. This was realized when ICAR-CMFRI, with the financial support of the Marine Products Export Development Authority, launched a ground-breaking research initiative in 2020 that produced India's first scientifically validated data on marine mammal abundance and bycatch. Under this research initiative ICAR-CMCRI conducted India's first-ever comprehensive marine mammal stock assessment in collaboration with MPEDA, Fishery Survey of India (FSI) and ICAR-Central Institute of Fisheries Technology. The findings of this research initiative, showed that the estimated annual bycatch of marine mammals is well below the permissible limit, confirming that Indian marine fisheries operate within sustainable levels.

- Mariculture Initiatives – Not just in capture fisheries research, ICAR-CMFRI has also proven its strength in mariculture research through its accomplishments in standardizing the breeding and larval rearing of 13 food fish species, advancing marine and coastal cage farming systems, seaweed cultivation, mussel and oyster culture, ornamental fish culture and Integrated Multi-Trophic Aquaculture (IMTA) integrating fish, mussels, and seaweed. Recently, the institute achieved success in the breeding and seed production of golden trevally *(Gnathanodon speciosus)* and giant trevally *(Caranx ignobilis)* as well as in two ornamental species lemon coral goby *(Gobiodon citrinus)* and talbot's demoiselle *(Chrysiptera talboti)*. The research efforts of ICAR-CMFRI were recognized by the Dept. of Fisheries, Govt. of India when it designated the Mandapam Regional Centre as a Centre of Excellence for Seaweed cultivation, for the holistic development and promotion of seaweed culture in the country. The centre was also recognized as a Nucleus Breeding Centre for Marine Fish Species by the Dept. of Fisheries, Govt. of India, a testament to the mariculture accomplishments of ICAR-CMFRI.

- Marine Biotechnology - The institute is a national leader in the nutraceutical domain, commercializing products derived from seaweeds and green mussels, to address lifestyle diseases. Other accomplishments include the discovery of PhPV1.2, a lytic bacteriophage targeting *Vibrio parahaemolyticus*. The whole genome of a number of species has been sequenced. Established two immortal fish cell lines from *Cromileptes altivelis* and a novel brain cell line from *Premnas biaculeatus*. Aqua feed innovation progressed with the commercialisation of black soldier fly larval protein-based fish feed. Research on whole genome sequencing of various marine species, has improved our knowledge of genetic stock structures and marine biodiversity.

- Climate Change - The institute is actively involved in climate change studies, with research focussed on associating environmental variables with distribution of marine fish, predator-prey dynamics, thermal adaptability of marine finfish species, effect of environmental variables on seaweed growth and phytoplankton, all of which will be instrumental in predicting the impact of climate change on marine flora and fauna. An assessment of the carbon footprint was conducted by the institute, with the results indicating that emissions from the marine fisheries sector of India are 16.3% lower than the global average, improving our understanding of the impact of fisheries on the environment.

- Marine Socio-economics - In the socio-economic domain, ICAR-CMFRI spearheaded initiatives for gender inclusion, integrating 145 transgender stakeholders into fisheries microenterprises. The institute assessed 120 fishing centres and enabled the development of a well-being index for migrant fishery workers and evaluation of the labour demand-supply gap in the sector. The economic valuation of marine landings of 2024 indicated ₹ 62,702 crores at landing centres and ₹ 90,104 crores at retail markets, reflecting notable growth from the previous year. These assessments, along with key economic indicators, contributed to a deeper understanding of sectoral performance, supporting policy frameworks for sustainable fisheries.

- Policy Inputs – ICAR-CMFRI has brought forth several documents to aid in science-based policy development for the sustainability of the marine fisheries sector of the country. These include the Green Certification Guidelines of marine ornamental species in consultation with the Marine Products Export Development Authority for wild collection and captive breeding so that dependence on collection of specimens from coral reef habitats could be gradually reduced. The institute had published policy guidance documents for Kerala, Tamil Nadu, Karnataka and Andhra Pradesh as well has been instrumental in the development of the National Plan of Action for Sharks in India. The Non-Detrimental Findings of CITES listed sharks and rays brought out by the institute provide an overview of the status of these species in India. ICAR-CMFRI had also introduced the Draft National Mariculture Policy 2019 (NMP, 2019), projecting a transformative path towards sustainable marine fish production. The recently released NITI Aayog report "India's Blue Economy: Strategy for Harnessing Deep-Sea and Offshore Fisheries" also had significant contribution from ICAR-CMFRI.

- Biodiversity Conservation – Through its research efforts on marine biodiversity of the country, 248 new marine species across various taxa have been added to science. In addition to indexing the marine biodiversity of the country, the institute has also taken significant steps for conservation of ETP species including contributions to the IUCN's Important Shark and Ray Areas (ISRA) compendium, modification to the marine shark and ray species under the Wildlife (Protection) Act of India, Non-Detrimental Findings for CITES Appendix listed sharks and rays, etc.

- Habitat Restoration – Marine habitat restoration and artificial reefs (ARs) have become synonymous in India, chiefly due to the efforts of ICAR-CMFRI in deploying artificial reefs along the coastline of the country. ARs are submerged structures that mimic natural reefs, providing habitat for fish and other marine life. When managed sustainably, they contribute to an increase in fish populations, promote biodiversity, and support recreational diving and fishing. These efforts span four states, encompassing 132 locations and 26,575 reef units, covering a total area of 0.37 million square meters (37 ha). The results of these endeavours have led to a 17 to 30% increase in fishery yields, demonstrating the positive impact of habitat restoration on marine resources. Following the success of ICAR-CMFRI's AR initiatives, the Dept. of Fisheries, Govt. of India has undertaken AR deployment along all coastal states of India on a large scale.

Emerging Futuristic Initiatives

ICAR-CMFRI is constantly striving to improve its research outputs through the use of new technologies and developments in the marine fisheries arena. The institute is making strides in the use of Geographic Information Systems (GIS), remote sensing, artificial intelligence (AI) and many more technological innovations to bring forth scientifically robust outputs, that will not only improve fisheries management but will also ensure improved livelihoods to the stakeholders. Some of these initiatives are detailed below:

- Marlin App and Artificial Intelligence – ICAR-CMFRI developed an Android Mobile App "MARLIN@CMFRI" for comprehensive media sharing, stands at the forefront of revolutionizing marine fishery research and identification/assessment efforts in the Indian Exclusive Economic Zone (EEZ). This cutting-edge App is designed to empower users with a platform for uploading high-quality digital images related to marine fish landings and facilitates the development of a comprehensive database for advanced AI-driven automated marine fishery resources identification system. The App allows for seamless photo upload, provide details of species and geotagging. By bridging the gap between citizen science and cutting-edge technology, MARLIN@CMFRI transforms every user into a crucial contributor to the understanding and preservation of marine biodiversity in the Indian EEZ.
- Carbon Credits – India is moving towards Voluntary Carbon Markets (VCM) in Fisheries and Aquaculture and is keen on developing a framework for VCM implementation in these two sectors. ICAR-CMFRI is one of the partners in the VCM initiative and is moving ahead with proposals for developing carbon projects in the marine fisheries sector. There are several potential carbon credit opportunities in the fisheries sector including restoration of mangrove afforestation and reforestation, seagrass beds and wetland conservation, use of renewable energy, etc. which the institute is exploring further for implementation of VCM.
- Developing Standards for Marine Biodiversity and Ecosystems - A dedicated panel under the Ecosystem and Environment Division Council (EEDC) of the Bureau of Indian Standards (BIS) will be established with ICAR-CMFRI as the nodal agency to develop national standards and guidelines for sustainable marine fisheries and ecosystem management. The panel will formulate standards for fish production augmentation using artificial reefs and integrate habitat conservation into marine spatial planning to support ecosystem-based fisheries management. It will also develop guidelines for managing deep-sea fisheries and sustainable harvesting practices for aquatic flora and fauna. Further, it will promote eco-labelling and sustainable harvest certification systems to enhance seafood traceability and market access. The initiative will also include frameworks for eco-restoration of degraded marine ecosystems and blue carbon accounting for inclusion in national climate strategies. Additionally, community-led fisheries co-management frameworks will be developed to ensure inclusive governance and stakeholder participation. Through this initiative, ICAR-CMFRI will provide leadership in setting science-based standards that balance resource utilisation with long-term ecological sustainability.

Ecosystem Approach to Fisheries Management – The Ecosystem Approach to Fisheries Management (EAFM) is an approach to sustainably manage fisheries in a holistic manner by considering the entire ecosystem. This approach is built on balancing ecological and human well being through good governance. ICAR-CMFRI in partnership with the Bay of Bengal Program IGO is currently developing an EAFM plan for the Coringa mangrove ecosystem in Andhra Pradesh. Recognizing the relevance of EAFM in ensuring long-term sustainability of resources and ecosystems, the institute is developing an EAFM network to enable focussed research on EAFM in India.

ICAR-CMFRI has been supporting India's vibrant marine fisheries sector through its innovative and pertinent research activities and outputs. Not resting on its laurels, the institute is constantly striving to improve its activities for the sustainable development of the marine fisheries sector of India. In the era of digital innovations and AI, the future for marine fisheries research is quite good where we hope to combine the prowess of Artificial Intelligence with marine ecology and biology, thereby conducting innovative research. Armed with its extensive past research outputs and emerging research initiatives, ICAR-CMFRI is already marching forth into the "digital marine" future to ensure that India's marine resources are utilized sustainably and the well-being of the stakeholders is secure.

Technological Innovations of the National Institute of Ocean Technology for Sustainable Utilization of Marine Resources

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The National Institute of Ocean Technology (NIOT), under the Ministry of Earth Sciences, Government of India is carrying of research and development in the field of ocean science and engineering technology in order to develop indigenous, reliable technologies to address the engineering challenges as associated with the exploration and sustainable utilization of ocean resources within India's Exclusive Economic Zone (EEZ). Guided by its mission to design, develop and deliver world-class ocean technologies, NIOT provides value-added technical services and contributes to building national capabilities for ocean resource and environmental management.

The institute's major research and development areas includes; Coastal and Environmental Engineering, Ocean Observation Systems, Ocean Structures, Energy and Freshwater, Marine Sensor, Ocean Electronics, Ocean acoustics, Deep Sea Technology, Deep Sea Mining, Marine Biotechnology and operation and maintenance of Ocean research vessels.

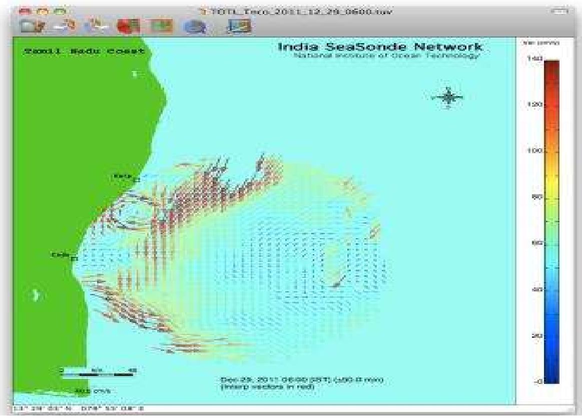
Coastal and Environmental Engineering (CEE):

Aims to develop the state-of-the-art technology in coastal infrastructure development through field observation, numerical modeling and engineering application, focusing on coastal protection for developing solutions for sustainable management of coastlines with potential stakeholder interests like industry, fishing, tourism etc.

- Successfully demonstrated segmented submerged breakwaters using sand-filled geosynthetic tubes at Kadalur, Tamil Nadu-the first of its kind in India's open coastal waters.
- The eco-friendly shore protection at Kadalur resulted in a 40m wide beach at Chinnakuppam, beach growth at Periyakuppam and Aazhikuppam
- Performance assessments have been conducted along the Indian coast to support the design of environmentally friendly coastal protection structures, addressing industrial, tourism and fisheries sector needs.
- Shoreline protection designs were completed for Bommayapalayam and Mahabalipuran coasts.
- Shore protection studies were undertaken for the Thiruvananthapuram coast, including Poonthura, Valiyathura and Shanghumugham, using numerical modeling and sediment transport analysis.

Growth of beach at Chinnakuppam, Tamil Nadu

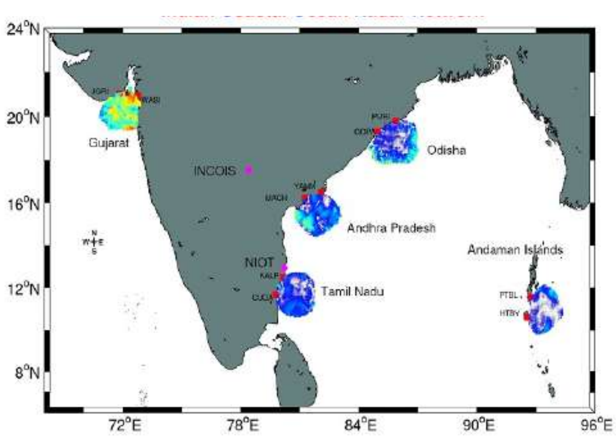
Growth of beach at Periyakuppam Tamil Nadu



Surface current measurements using HF Radar

Development of design criteria for extreme environment by assessment of waves, currents and tide parameters Coastal Monitoring System

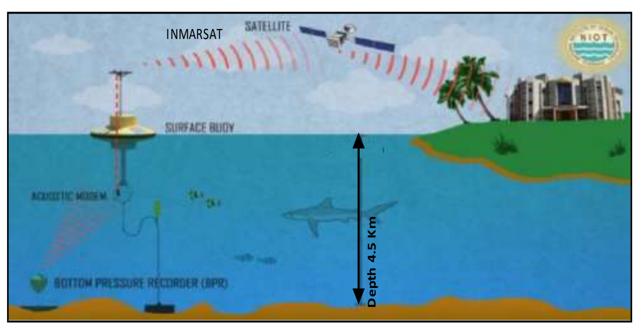
- Established a coastal monitoring system to provide real-time tide and met-ocean data along the Indian coast through 6 tide and 8 weather stations. Data are transmitted via GPRS to an FTP server in real time.
- Tide analysis from 19 stations (since 2010) led to a tide prediction tool for tidal forecasting and model boundaries.
- Developed and validated a North Indian Ocean wave model (1998-2012) using ECMWF wind fields and NIOT, INCOIS & NIO data.
- The Indian Coastal Ocean Radar Network (ICORN) operates 10 HF radars under Ocean Observation Network (OON) program of MoES, with data shared via NIOT and INCOIS.



Indian Coastal Ocean Radar Network (ICORN)

Ocean Observations Systems (OOS) - Address the indigenous development of moored buoy network, operation, maintenance related technologies for real-time ocean data collection in the Indian seas. OOS also supports autonomous ocean observation through indigenously developed systems such as the Submerged Tsunami Buoy, Integrated Marine Surveillance System, and Arctic moorings, enhancing India's capability in real-time ocean monitoring and climate prediction.

The observed data are then transmitted through satellite and location reference, in synoptic hours, to the state-of-the-art shore station facility CORNEA - Centre for Ocean Realtime iNformation viEw and Archives at NIOT, Chennai. CORNEA complies with global tier III Data Centre standards and Integrated designs for scalability, safety, clean and a highly secured environment



Ocean data buoy model

Data buoy

- Operation and maintenance of twelve (12) OMNI buoys, four (4) coastal buoy systems, one (1) CAL-VAL buoy system, and two (2) Tsunami buoy systems. Besides, one (1) IndARC mooring at Kongsfjorden, Norway, one ADCP mooring and a Directional Wave Rider buoy off Chennai.
- Indigenously developed Tsunami Bottom Pressure Recorder (BPR) - Sagar Bhoomi was successfully developed & deployed off Chennai.
- Real-time data transmission to INCOIS every three hours via satellite, supporting cyclone and tsunami monitoring.
- RAMA collaboration with NOAA for monsoon and climate research, enabling open data access via the joint OMNI-RAMA portal.
- Calibration Test Facility established at NIOT for sensor validation as per WMO–RMIC standards

Ocean Structures (OS) - research provides innovative engineering solutions for offshore installations, addressing both institutional and industrial needs. Major areas of focus include Low Temperature Thermal Desalination (LTTD) plants, Offshore Structural technologies and demonstration of Shore Protection Measures.

Established 1.5 Lakh liters per day capacity Low Temperature Thermal Desalination plants in Six Islands of Union Territory Lakshadweep to meet freshwater needs of island communities.

Numerical models were constructed to study the shoreline response for beach nourishment with various configurations of retaining structures. Based on these results a northern nearshore reef and southern offshore reef along with beach nourishment was planned. Design and deployed a wedge reef, in the shape of a triangle with a base width of 50m and a length along the spine of 60m. Successfully launched appx. 900-ton wedge shaped steel reef into the open sea, positioned and ballasted.

Seawater intake and LTTD plant at Lakshadweep Islands

- Designed and installed a 900t near shore steel reef with beach nourishment at Puducherry, resulting in a beach width gain of ~60m.
- Conducted feasibility studies for offshore and turbine substructures in the Gulf of Khambhat and Gulf of Kutch.
- Developed the Varshini-1 Air Conditioning and Water Generation System, capable of producing 65 L/day of freshwater while providing 1.5 TR cooling

Energy and Freshwater (EFW): Focus on development of technologies to generate electricity and produce potable water using ocean energy sources such as waves, currents, and thermal gradients. Focal areas include development of technologies for Low Temperature Thermal Desalination (LTTD) using coolant water discharge from thermal power plant and offshore deep-sea cold water, wave energy conversion using floating devices such as navigational buoy, marine hydrokinetic turbine development, heat exchangers for LTTD and turbines for Ocean Thermal Energy Conversion (OTEC) are the focal areas of research.

- Development of turbines for harnessing energy from OTEC /Wave energy/Ocean currents which could be standalone units or used to power LTTD plants or small loads
- A 1 MLD offshore barge-mounted LTTD plant was successfully demonstrated off Chennai.
- Wave-powered desalination and navigational buoy successfully demonstrated at Vizhinjam and off Chennai
- Backward Bent Ducted Buoy (BBDB) and Wave Powered

Navigational Buoy (WPNB) successfully tested and transferred to industry.

Barge mounted 1 MLD LTTD plant

Wave powered Navigational buoy

- Installation and commissioning of a 2x1 MLD LTTD plant using condenser reject heat in Tuticorin Thermal Power Station and NCTPS, Chennai for producing the drinking and industrial quality water
- OTEC-powered desalination plant of 100 m^3/day capacity under implementation at Kavaratti for sustainable freshwater generation with minimal carbon footprint.
- Demonstrated Sea water Lantern 'ROSHINI' and Technology transferred to numerous Industries.

Deep Sea Mining (DSM) – mandated to develop an Integrated Mining System for mining polymetallic nodules, cobalt rich manganese crust and hydrothermal deposits from a depth of 5000-5500 m in the Central Indian Ocean Basin (CIOB) for extraction of economically valuable metals such as Copper, Cobalt, Nickel and Manganese which are viewed as potential resources for the depleting land resources and increasing demand .

- An integrated underwater mining system was developed and demonstrated at 510m depth off Malvan to validate mining and riser concepts.
- Dee-sea soil testing systems, capable of operation up to 6000m, have been successfully deployed for real-time seabed property measurement.
- Pumping and riser studies have been carried out to understand slurry flow characteristics and scaling for 6000m operations.
- Deep-sea locomotion trials at 5270m depth validated India's first tethered seabed mining vehicle, establishing NIOT's capacity for deep-sea engineering under extreme hydrostatic pressures and temperatures.

Deep Sea Technology (DST) - aimed towards develops manned and manned and unmanned underwater vehicles for the exploration and exploitation of deep ocean mineral resources such as poly-metallic manganese nodules, gas hydrates, hydrothermal sulphides, etc and other oceanographic and industrial applications

ROV ROSUB 6000 concept

ROV ROSUB 6000 deployment

- Developed 6000 m depth rated scientific manned submersible and depth rated work-class deep water ROV ROSUB 6000, deployed for mineral, gas hydrate and hydrothermal exploration (Fig. 3a).
- Developed 500 m shallow/polar ROV PROVe for coral reef studies, biodiversity assessment, ice coring, and search/recovery operations (Fig. 3b).
- Designed deep water Wire-line Autonomous Coring System (WACS) to drill up to 100 m and recover cores from 3000 m depth for gas hydrate validation.

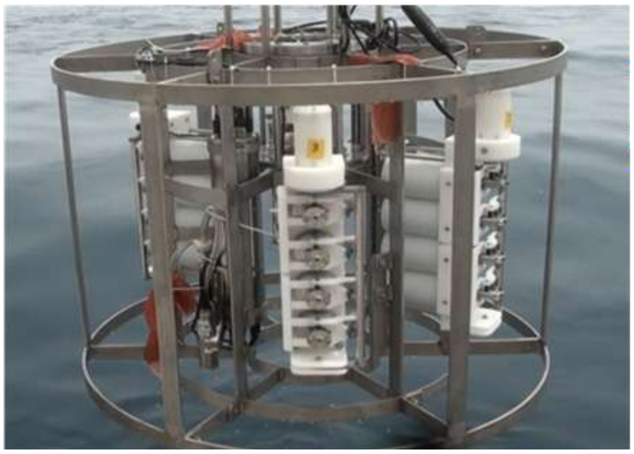
Autonomous Underwater Vehicle

Manned Submersible model

- NIOT-MoES realized Deep water Autonomous Underwater Vehicle (AUV) from M/s Kongsberg Maritime, Norway for deep ocean scientific research
- High resolution mapping with scientific payloads and photography was conducted at Polymetallic Manganese Nodule field at Central Indian Ocean onboard ORV Sagar Nidhi.

Marine Biotechnology (MBT) Programme focuses on harnessing marine living resources using advanced biotechnological tools, with major focus on marine algal biotechnology, marine microbial biotechnology, open-sea cage culture and ballast water treatment. The group aims to develop sustainable solutions for large-scale utilization of marine bio-resources to support food security, industry and environmental sustainability.

- Pilot scale outdoor mass scale experiments, for four species of high lipid yielding marine microalgae namely, *Chlorella vulgaris, Chlorella sorokiniana, Chlorella pyrenoidosa,* and *Neochloris aquatica* and were carried out and a maximum biomass production of 0.76 g/L/d, with the 25.53% lipid was achieved in *C. sorokiniana*.
- A cost-effective DC powered electro-flocculation method with 98 % efficiency and power consumption rate of 0.32 kWh/Kg for harvesting the microalgal was developed.
- Production of pharmaceutical important lutein (used for treatment of age-related macular degeneration) from marine microalgae was and transferred to industry
- Developed 650 pressure rated high pressure retainable water sampler and 350 bar pressure rated higher pressure microbial culture system for isolation and culture of deep sea piezophilic microbes.



High pressure sampler 650 bar pressure rated

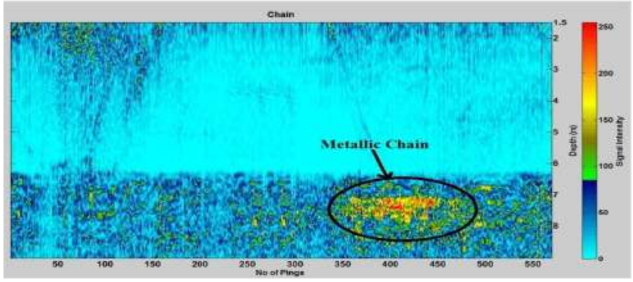
High pressure fermenter 350 bar pressure rated

- Isolated 348 deep sea piezotolarent microbes which includes bacteria, fungi, and actinomyces from 1000 – 4500 m depth
- Isolated novel bioactive secondary metabolite such as multiple prodiginines, tripyrrole, grisiofulvin, spirobenzofuran, pyrazine, piperazinedione, sequesterpenes deratives, l-asparaginase, lipopeptide surfactant, cyclic peptide and ectoine enzyme.
- HDPE floating collar cages of 9 m diameter with multipoint mooring system were developed and tested in different environmental conditions at Olaikuda (Tamil Nadu), Kothachathram, Tuplipalam (Andhra Pradesh) North Bay (Port Blair), and Kumta, Karnataka.
- Demonstrated open sea cage culture 6 species of marine finfishes seabass, cobia, milk fish, parrot fish, carangids and siganids in open sea cages.
- Demonstrated nursery rearing of seabass and cobia fish fingerling in the indigenously developed 2 m diameter nursery cages deployed within the open sea cages.
- Established India's first land-based tropical Ballast Water Treatment Test Facility at NIOT seafront facility at Pamanji, supporting IMP D2 regulation compliance.
- Developed and deployed large number of reef structures along Odisha and Tamil Nadu coast and large number of FADs in Lakshadweep and Andaman to promote biodiversity and sustainable fisheries.

Marine Sensor Systems (MSS) focuses on indigenous development of acoustic sensors, imaging sonar systems and underwater signal processing, serving both national and industrial needs. Its activities align with the "Made in India" initiative, supporting indigenous development of advanced marine technologies.

- Designed a 2D/3D Sub-Sea Bed Imaging Sonar for pipeline and archaeological structure imaging with decimetre resolution.
- Developed Side Scan Synthetic Aperture Sonar (SSS) with interferometric height measurement and high-resolution imaging capability up to 30m depth.
- Implemented advanced signal processing algorithms for improved sonar image quality and motion compensation.

Acoustic Sub Bottom Profiler



Metal chain buried in Sea bed

Broadband transreceiver

Acoustic transmitter

Ocean Electronics (OE): research is focused in developing new ocean observation technologies and has developed profiling floats, Drifter with INSAT Communication, C- profiler, WXCTD, Ocean Glider, Self-sustainable profiling systems using Ocean thermal energy and automatic biomass estimation system and feeding system for open sea cages.

- Design and development of Sea Glider with buoyancy engine, communication system, navigation systems, electronic system, power module.
- Design, development of "C" profiling system and demonstrated the Tow fish interfaced with CTD sensor collecting mixed layer ocean parameters while vessel on move.
- Design and developed non-contact type Conductivity sensor tested & data validated with seabird sensor.
- AI based Fish bio-mass estimation system is developed, tested and validated for open sea cage fish culture
- Drone based Ocean data collection with CTD, sea water sample collection, Beach topography & High tide line mapping demonstrated.

Deep-Sea Autonomous Underwater Profiling Drifter (DAUPD)

Non-Contact type Conductivity sensor

Operation of C-Profiler

Ocean Research Vessels: NIOT fleet of deep sea and coastal research vessels cater the of technology testing, demonstration through the state of art ice class vessel ORV Sagar Nidhi, and oceanographic and buoy tendering vessel ORV Sagar Manjusha and coastal research vessels Sagar Tara and Sagar Anvasika enhance research and exploration competencies for the benefit of the country.

Sagar Nidhi

Sagar Manjusha

Empowering the Blue Economy with Science and Technology-based Ocean Information

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The ocean, though a source of immense wealth, remains unpredictable and challenging. For those whose livelihoods depend on it, such as fishermen, port operators, shipping companies, and coastal residents, accurate and timely information on the ocean is not a luxury, but a necessity. Yet, to the other section of the population, the significance of ocean information services often remains invisible. Put simply, 'information is the light that guides humans through the darkness of uncertainty'. In the context of the ocean, this light of information is provided through the integration of ocean observation systems, modeling, and forecasting technologies that help predict conditions ranging from wave heights to potential fishing zones and coastal hazards.

Over the past two and a half decades, INCOIS has been at the forefront of this effort, transforming scientific data into actionable insights for millions of ocean-stakeholders. Among its multitude of services, the Marine Fishery Advisory Services are a testament to India's leadership in applying cutting-edge science to grassroots development. These services integrate data from satellites, numerical ocean models, and in situ observations to generate advisories that help fishermen plan their ventures safely and efficiently.

Ocean Information Services and Blue Economy

India's economy is advancing at an extraordinary pace, steadily outcompeting several global powers in recent years. The recent revision of the GDP growth forecast by Reserve Bank of India's reports a raise from 6.5% to 6.8% for 2025-26; signals the resilience and vitality of the country's economic trajectory. At the core of this growth lies the power of the nation's human capital, coupled with innovation in technology and a national vision rooted in 'Atmanirbhar bharat'. The strategic use of technology, guided by visionary governance, has bridged critical developmental gaps, fueling India's transformation into one of the world's fastest-growing major economies.

Among the key pillars supporting this transformation is the Blue Economy- a sector of immense promise that harnesses the power of ocean resources for sustainable development. Highlighting a recent article by Dr. Jitendra Singh, Minister of State for Science and Technology, the Hon'ble Prime Minister Shri Narendra Modi underscored that how the recent initiatives such as the Sagarmala Programme, Deep Ocean Mission, and Harit Sagar Guidelines collectively strengthen India's commitment to harnessing ocean resources responsibly while empowering coastal communities and driving innovation.

The journey toward a "Viksit Bharat 2047": a developed India, requires renewed focus on the nation's greatest untapped potential of its vast oceanic domain. The Blue Economy encompasses both traditional sectors, such as fisheries, ports, and shipping, and frontier fields, such as marine biotechnology, renewable energy, and deep-sea exploration. India's ~11,000 km coastline, its ~2.02 million square km Exclusive Economic Zone (EEZ), and its rich marine biodiversity together provide a natural foundation for ocean-based growth that is both inclusive and sustainable.

The informed and judicious use of ocean resources stands as an evident example of how technology can reach end users, influencing national prosperity and the well-being of coastal communities, particularly fishermen, the sentinels of our shores. As the Prime Minister remarked during the launch of Oceansat-3 (EOS-06), "the advances in the world of space technology will help us to better predict cyclones and promote our coastal economy." This vision finds practical realization in the mission of INCOIS, which serves as a bridge between advanced science and coastal livelihoods.

The Impact of Ocean Information Services on the Fisheries Sector

The Potential Fishing Zone (PFZ) advisory service is the pioneering program by INCOIS that guides fishermen to probable fishing grounds using satellite-derived ocean parameters such as sea surface temperature, chlorophyll concentration, and ocean currents. By indicating locations of likely fish aggregation, PFZ advisories help fishermen reduce their search time, fuel consumption, and operational costs. The economic and environmental impact of this service is substantial. Further, the species-specific advisories for Tuna and Hilsa have also been benefiting the fishermen by enabling more planned and sustainable fishing operations. Studies indicate that PFZ advisories have helped reduce fuel usage and significantly lower operational expenses while simultaneously decreasing carbon emissions, a critical contribution to India's climate change mitigation goals and Blue Economy targets. Beyond direct economic benefits, ocean state forecasts enhance safety at sea by allowing fishers to better plan their trips based on the ocean weather, ensuring safety at sea. In addition, INCOIS has expanded its portfolio to include Algal Bloom Information Services, which monitors and forecast harmful algal bloom events that can affect fisheries, aquaculture, and coastal water quality. The Coral Bleaching Alert Services offer early warnings to help protect India's coral reef ecosystems from rising sea surface temperatures and climate-induced stress.

Ocean Information Services Beyond Fisheries- The Wider Economic Web

The importance of ocean information services extends far beyond fisheries. The shipping and port sectors, which handle more than 80% of global trade by volume, require accurate and timely marine forecasts. Every product that reaches our homes, from electronics to raw materials, has, at some point, journeyed across the ocean. Ensuring the safe and efficient movement of maritime traffic is thus fundamental to both global and national economies. By providing data on sea-state conditions, wave height, currents, and ocean weather forecasts, INCOIS's ocean information services help support decision-making for logistics, naval operations, and offshore industries and safeguard vessels and reduce transit risks, In this way, ocean information forms the hidden infrastructure that sustains India's trade and commerce.

Moreover, the Tsunami Early Warning Centre (ITEWC) has established India as a global leader in disaster preparedness. Apart from providing services to the Indian coast, it also provides regional tsunami alerts to 24 countries across the Indian Ocean, showcasing how ocean information can cross national boundaries to protect lives and livelihoods.

Technology, Innovation, and Inclusivity: The INCOIS Approach

INCOIS's journey aligns with the efforts and ability to integrate multiple disciplines, from satellite remote sensing, oceanography to data science and community outreach. By merging scientific observations, modeling, and citizen science, the organization has created a dynamic information ecosystem that evolves continuously to meet stakeholder needs.

Through mobile-based applications, SMS alerts, and dedicated advisories in regional languages, ocean information has been made accessible even to small-scale fishermen in remote villages. These efforts underscore how technology-driven inclusivity can bridge social and economic lacuna, turning science into a tool for empowerment.

The Future of Ocean Information and the Blue Economy

As India advances towards its Vision 2047, the role of ocean information services will become even more critical. The growing scale of offshore renewable energy projects, deep-sea fishing, mining, marine biotechnology, and sustainable marine aquaculture will demand higher-resolution data, real-time forecasting, and integrated decision-support systems.

To meet these emerging needs, INCOIS is strategizing its Vision 2047 roadmap, aimed at enhancing observation networks, numerical modeling capabilities, and user-centric service design. The Centre's future priorities include High-resolution Ocean modeling, Customized information products, early warning systems for coastal hazards and extreme weather events, support to renewable energy and offshore infrastructure through ocean state analytics, integration of marine Carbon Dioxide Removal (mCDR) strategies to aid climate change mitigation.

Summary:
Embracing the Blue Potential

Blue Economy in the Indian context is more than a developmental agenda; it is a philosophy that harmonizes growth along with sustainability. From empowering fishermen through PFZ advisories to safeguarding the coastal communities, maritime trade and advancing marine research, ocean information services have invisibly become the backbone of coastal resilience and economic vitality.

As India's economy sails ahead with renewed trajectories, the ocean, our great untapped frontier, holds the key to sustainable prosperity of the country. With the collective strength of science, innovation, policy vision, and community engagement, India is well on course to turn this aspiration into reality- charting a blue pathway toward a sustainable and prosperous Viksit Bharat by 2047.

Digitisation of the Marine Fisheries Capture Sector of India: building a compliance-ready, science-first system

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India's marine capture fisheries are moving from paper records and periodic surveys to a continuous, machine-readable stream of information that connects vessels, landing centres and markets. The point of this transition is not technology for its own sake. It is to meet binding sustainability obligations, close management gaps in a tropical, multi-species setting, and strengthen the legitimacy of rules that determine who fishes, where, and how much. While the Ministry of Fisheries, Animal Husbandry & Dairying has launched significant digital initiatives, further digitization is crucial to create a seamless "net-to-plate" traceability system. Foundational steps like the ReALCraft portal for vessel registration and the Vessel Communication and Support System for tracking, safety and disseminating Potential Fishing Zone (PFZ) advisories have modernized at-sea operations. The planned onboard electronic observer system for catch monitoring by Fishery Survey of India will be a critical next step. Integrating small-scale fisheries into a holistic digital framework is essential to close traceability gaps, enhance food safety, and fully empower Indian exporters to meet the increasingly stringent data demands of global markets. This article maps the state of play, explains why end-to-end digital architecture matters, and sets out a pragmatic pathway to scale—anchored in what India has already built and what remains to be done.

The Legal Baseline that Digitisation must Satisfy

International law is explicit about stock sustainability and the evidence required to underpin it. The United Nations Convention on the Law of the Sea obliges coastal States to determine allowable catch in their EEZ and to maintain or restore stocks based on the best scientific evidence; similar duties apply on the high seas. The 1995 UN Fish Stocks Agreement adds the precautionary approach, requires cooperation on stock assessments and data exchange, and places concrete monitoring and compliance responsibilities on flag States. For straddling and highly migratory species in the Indian Ocean, the Indian Ocean Tuna Commission's conservation and management measures are assessment-linked and demand that members not only contribute data but also act when reference points are breached. The FAO Compliance Agreement orients flag-state authorisations toward RFMO rules. The 2022 WTO Agreement on Fisheries Subsidies introduces an incentive by conditioning certain subsidies on credible proof that they do not contribute to overfishing or that remedial measures exist where stocks are overfished. The export market regulations such as European Union IUU Regulation and the United States Seafood Import Monitoring Programme (US SIMP) are compelling the industry to move towards greater transparency, enhanced traceability, and the adoption of modern data management practices. India also reports the proportion of sustainable stocks under SDG indicator 14.4.1 and draws normative guidance from the FAO Code of Conduct for Responsible Fisheries, the Small-Scale Fisheries Guidelines and the Voluntary Guidelines on Flag State Performance. Read together, all these instruments make continuous, auditable data a compliance requirement.

Why do Tropical Fisheries Need a Different Data Strategy?

Unlike temperate systems dominated by a few target species, tropical fisheries are species-rich, dynamic, and are exploited by multiple gears. Hence, stocks may need to be defined at the level of assemblages and assessed as management or assessment units nested within or across broader biological populations. That reality complicates classical, single-species assessment and pushes the system toward methods that can make use of multiple, heterogeneous data streams—catch, effort, length-frequency, habitat and climate—updated at short intervals. Depending on the management strategies, even such fishery management units can have multiple species caught by the same gear. Hence, tropical multi-species fisheries need a portfolio of assessment methods, not a single canonical model. They lie across a spectrum of mathematical models starting from data-poor catch-only and per-recruit approaches, length-based and surplus-production models for medium data situations, and age-structured, integrated models such as Stock Synthesis 3 (SS3), ecosystem based tools such as Ecopath-Ecosim and MICE for data rich situations.

From Analog Fragments to a Single Digital "trip record"

A workable architecture begins at sea and ends with trade. Each fishing trip should instantiate a canonical digital record that binds the vessel identity, crew, gear and effort to spatial tracks and to verifiable accounts of catch and bycatch. E-logs, E-monitoring, Satellite Remote Sensing, Management Simulations and Web-based decision making platforms can form the component of such an schema.

Electronic Logbooks: Technique India can Absorb Immediately

E-logs are the fastest way to move from delayed, paper-based returns to near-real-time catch and effort data. Global practice includes tablet-based dockside and onboard collection. India also has systems in place such as apps developed by CMFRI - Marlin & FCSA. There can be lighter AI-assisted apps that automate species recognition and weight estimation, and a variety of platforms used elsewhere—from FISHER, mFish, EFICE, M-Catch, Sagara and Caribbean Fishery, to DiuSagar, NabhMitra and Ver Catch. Apps with payment record or programme-specific systems such as Blue Lobster, MPEDA Catch, TSER etc. can help fishers to benefit further. Hybrid systems like eCatch used in New Zealand and tools promoted by WorldFish can store data offline and upload them when the vessel is in the coverage area. As direct-to-cell services over low-Earth-orbit satellites mature, e-logs can move from store-and-forward synchronisation to at-sea updates even beyond mobile coverage. A single dynamic QR-coded lot integrating tripID and payment transactions carries that provenance into the supply chain, creating a custody trail that is intelligible to regulators and export markets alike. The adoption of such tools can be enhanced by integrating financial utilities—credit scoring and insurance—if privacy and governance are properly specified from day one.

Electronic Monitoring: Scaling Observer Coverage with Automation

Human observers are hard to deploy at scale across India's diverse fleet. Camera-based electronic monitoring (EM) offers a defensible alternative for measuring retained catch, discards, interactions with protected species and compliance with gear rules. The hardware choices can meet a range of budgets and data ambitions. Batch "record-then-review" storage is affordable but introduces latency. Edge computing with low-cost microcontroller solutions can perform intelligent capture to reduce footage; mid-range edge-AI built on Raspberry Pi 5 with Coral accelerator modules supports on-board species and length estimation; all-in-one AI boards (Coral Dev board) trade flexibility for tidy integration; and high-end systems built on NVIDIA Jetson deliver near-real-time, fully automated inference at higher cost. The Forward-Looking Infrared cameras can be best used for monitoring night operations. A pragmatic roadmap for India would start with high-priority fleets and gears, establish retention and handling rules that make image review meaningful, and adopt audit-based risk assessment rather than blanket 100% manual review. All such approaches only work with a clear regulatory and operational framework that sets roles for EM service providers, standards for camera placement and crew duties, and protocols for data review.

Remote Sensing: Effort Maps and Biomass Signals from Space

Digitisation should not stop at the gunwale. Integrating satellite remote sensing brings two complementary advantages: a synoptic view of fishing effort and a dynamic picture of the ocean itself. AIS, VMS and DoF installed transponders tracks can be used to increase traceability and security. Combined with night-time lights from VIIRS can resolve light-lure fleets such as squid vessels, while synthetic aperture radar can detect metal hulls regardless of weather and provide an external cross-check for spoofed or missing identity signals. Machine-learning analytics can then classify fishing events, enable effort standardisation in assessments, reconstruct navigation histories and flag anomalous behaviour that suggests transhipment or incursions. At the same time, ocean-colour products provide estimates of plankton biomass and primary productivity that can be linked to habitat-based predictions of species distribution, potential fishing zone advisories and productivity needed potential yield estimations.

Management Strategy Evaluation: Testing Rules Before they Touch the Water

Even the best assessment is not the end of the decision chain. Management Strategy Evaluation (MSE) allows India to test candidate harvest control rules and monitoring schemes against simulated populations and fleets before implementing them. A Stock Synthesis–based MSE stack (SSMSE) makes it straightforward to recycle existing assessments into policy-testing engines and to visualise outcomes with decision plots familiar to RFMO audiences, such as Kobe plots that track biomass and fishing mortality against reference points. Embedding MSE in India's rule-making process would make UNFSA's precautionary approach concrete and defensible.

Public-facing Transparency: Stock Status and Marine Atlases

Credibility improves when results are easy to find and interpret. Similar to CMFRIs Marine Fish Stock Status publication, Australia's digitised stock status reports is an example of how hundreds of assessments can be discoverable by species, gear and jurisdiction, and Tasmania's Marine Atlas shows how a web-gis map can bring together biophysical layers, threats and pressures in one place. India can adopt the same idea: a searchable, bilingual stock status portal that publishes methods, inputs and confidence grades; and an atlas that overlays dynamic oceanography, critical habitats and human activity. Such products do not only inform the public; they also satisfy reporting expectations under SDG 14.4.1 and demonstrate to trade partners that India's traceability rests on stock-level science.

Digital Twin of the Ocean: From Dashboards to a Living Model

A digital twin is not simply a dashboard; it is a continuously updated computational mirror of the ocean that ingests observational data and forecasts the near future. The EU-funded "Arcfish" initiative is a working template: integrate oceanographic, climatic and fisheries data into an open repository, run data assimilation and scenario engines, and expose policy-relevant outputs to managers and scientists. A National Digital Twin of the Ocean for India can connect INCOIS ocean state and productivity fields, CMLRE biodiversity data, ISRO satellite products, DG shipping and DoF vessel activity, FSIs survey and monitoring data, CMFRIs stock status and many other info such as genomic signals, changing climate etc. into a shared operating picture. It would also create the substrate for automated, observation-driven updates of assessments and harvest rules—turning policy into code and code into daily management.

A Realistic Implementation Pathway

In practice, India can begin by mandating a common vessel identifier and minimum data schema across all applications and by issuing a single QR-linked trip or lot record at landing. E-logs should be scaled in fleets where species identification is straightforward and married to AI-assisted classification where it is not. EM can be targeted first at high-impact gears and fleets. Satellite data should be wired directly into assessment and compliance workflows rather than treated as a parallel pilot. SS3 and SSMSE can be adopted as the default for stock assessment, with clear upgrade paths as data improve. Throughout, managers should insist that every new digital module—whether an app, camera or satellite product—exposes open, versioned APIs so that the "trip record" can be assembled without bespoke integrations in each state. These steps mirror the recommendations in the presentation and are precisely what global instruments expect when they call for "best scientific evidence," "cooperation on assessments" and effective monitoring, control and surveillance. Automated triage and auditing ensure data quality before it flows into assessment pipelines

Conclusion

Digitisation, done well, is simply the fastest way to make international law and domestic conservation goals actionable in a tropical, multi-species reality. The pathway—E-logs and EM for fishery-dependent data, satellite and ocean-colour products for effort and habitat signals, a model toolbox that spans CMSY to SS3, MSE to test rules, and an eventual digital twin to fuse it all—aligns tightly with India's obligations under UNCLOS, the UNFSA, RFMO measures and the WTO subsidies agreement. It also aligns with the everyday needs of fishers and administrators: safer trips, faster decisions, cleaner audits and a fair chance at both sustainability and competitiveness.

Five Decades of Catalytic Action in Marine Fisheries and Ecosystem Management: The Genesis and Mandate of the Bay of Bengal Programme (BOBP)

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The Bay of Bengal Programme, commonly known as BOBP, was initiated as an FAO field project in 1979. It included seven countries: Bangladesh, India, Indonesia, Malaysia, Maldives, Sri Lanka, and Thailand. Although Myanmar was never a full member, it was often involved in the programme's activities. Although the specific reasons or the fundamental theory of change behind BOBP are now less clear, it seems that the organisation's objectives and activities were driven by the potential of the Bay of Bengal and the fisheries sector to transform rural economies in these densely populated developing nations.

It should be noted that BOBP was not the first external fisheries intervention in the region. Instead, it was likely the most recent developmental initiative. The region's international and regional fisheries efforts date back to the founding of the Food and Agriculture Organization (fao) of the United Nations in 1945. During this period, many Asian countries, former colonies, were gaining independence. These newly sovereign nations inherited underdeveloped fisheries sectors, ill-equipped to meet their national goals of food security, employment, or growth. External support first materialised through the Colombo Plan in 1951, alongside the establishment of the Indo-Pacific Fisheries Council under Article XIV of the FAO Constitution, held in Baguio, Philippines, in February 1948. The IPFC later evolved in 1993 into the Asia-Pacific Fishery Commission, the largest regional fisheries organisation in the region. In 1967, the Southeast Asian Fisheries Development Centre (SEAFDEC) was established, covering countries around the eastern Bay of Bengal – Myanmar, Thailand, Indonesia, and Malaysia.

Despite having a regional institutional framework, BOBP was initiated as a donor-funded independent programme aimed at fostering the development of the fisheries sector from within. Similar to existing regional organizations, the Programme covered all fisheries sub-sectors, such as capture and culture fisheries. However, what set it apart in the early years was its emphasis on techno-economic development rather than resource management. Co-development, a term now widely recognized, was not popular at the time. However, BOBP practised co-development by bringing the government and other stakeholders together to tackle fisheries productivity issues, with BOBP providing guidance. These innovations, introduced by BOBP, have since become an integral part of the sector, and their influence is evident in the rapid transformation of the fisheries industry since the 1980s.

Transition from BOBP to BOBP-IGO

Following a resolution at the 1999 Phuket Advisory Committee Meeting, the BOBP was officially established as the Bay of Bengal Programme Inter-Governmental Organisation (BOBP-IGO) in 2003. This change elevated its role from being an externally-funded FAO project to a self-governing regional fisheries advisory organisation.

The BOBP-IGO, based in Chennai, India, mainly focuses on strengthening cooperation among its member nations—Bangladesh, India, the Maldives, and Sri Lanka—and offers technical and management advice to support sustainable coastal fisheries growth. Its primary goal is to ensure the long-term development and responsible use of coastal fisheries resources through environmentally sustainable practices and sound management strategies.

The organization acts as a regional "think tank" on current national and transboundary issues, providing a vital platform for tackling shared challenges. The BOBP-IGO's goals are clearly centred on:

- Increasing awareness and knowledge of the needs and benefits of marine fisheries management.
- Enhancing professional skills through targeted training and education.
- Transferring appropriate technologies for the development of the small-scale fisheries sector.
- Establishing a robust regional information network.
- Promoting the participation of women at all levels of the fisheries value chain.

This fundamental transition secured a regional commitment to the long-term stewardship of the Bay of Bengal's resources, establishing the institutional framework needed for collective action in marine fisheries and environmental management.

Pioneering Activities in Sustainable Marine Fisheries Management

The bulk of the BOBP's work, both in its FAO phase and as the BOBP-IGO, has been dedicated to improving the sustainability of the region's diverse fisheries, with a particular emphasis on the artisanal and small-scale sector, which forms the socio-economic backbone of coastal life.

During its early years (1979–1994), BOBP carried out pilot projects in member countries to promote technological and methodological advancements. These initiatives included the introduction of more fuel-efficient fishing vessels and gear, such as fiberglass reinforced plastic (FRP) boats and energy-saving sail technologies. Additionally, the Programme focused on improving post-harvest practices by encouraging better handling, preservation, and marketing of fish to minimise losses and increase earnings for fisherfolk.

A core function of the BOBP has been to address the escalating problem of overfishing and the unsustainable exploitation of shared fish stocks. This work involves:

- Conducting stock assessments involves facilitating regional consultations on the status of economically significant shared resources, including Hilsa shad (Tenualosa ilisha), Indian mackerel (Rastrelliger kanagurta), and various Tuna and Scad species. These assessments offer the scientific evidence needed to inform management actions such as setting fishing quotas or enforcing seasonal bans.
- The BOBP-IGO has played a key role in coordinating the creation of a Regional Plan of Action to Fight Illegal, Unreported, and Unregulated (IUU) Fishing, which aims to harmonise national policies and surveillance initiatives.
- Regular global and regional assessments of fishing fleets are conducted to deliver data-informed insights into the economic sustainability and environmental impact of various fishing activities.

Promoting the Ecosystem Approach

In its current operation, the BOBP-IGO champions the adoption of the Ecosystem Approach to Fisheries Management (EAFM). EAFM is a holistic paradigm that recognizes the complex interdependencies between human activities, fish populations, and the environment. This represents a significant shift from traditional, single-species management. Through regional workshops and intensive training modules—such as the widely disseminated Essential EAFM course—the BOBP empowers resource managers to:

- Balance human needs for resources with ecosystem well-being.
- Incorporate environmental and social impacts into fisheries planning.
- Implement management strategies that are resilient to external shocks, like climate change.

These focused efforts on resource management form the bedrock of the BOBP's mission, transforming it into a scientific and technical advisor committed to securing the long-term biological and economic health of the Bay of Bengal's marine living resources.

The BOBLME Project: A Holistic Approach to the Ecosystem

To evolve from an advisory role to an ecosystem steward, the BOBP-IGO took on a central role as an executing partner in the groundbreaking Bay of Bengal Large Marine Ecosystem (BOBLME) Project. Funded mainly by the Global Environment Facility (GEF) and carried out by the FAO, this project signified a significant regional commitment to adopting a cooperative, ecosystem-based management approach for the entire Bay of Bengal.

The BOBLME Project was initiated with the understanding that the key threats to the Bay are transboundary, necessitating coordinated efforts among all littoral nations. During its first phase (2009–2015), the project effectively identified four major concerns shared across the region, which serve as the foundation for the entire management approach.

- Overexploitation of Marine Living Resources (Overfishing): The key threat to fish stock sustainability.
- Degradation of Critical Marine Habitats: Loss of crucial nursery and breeding grounds (mangroves, coral reefs, seagrass).
- Marine and Coastal Pollution: Contamination from land-based and sea-based sources.
- Socio-economic Vulnerability of Coastal Communities: The high dependence and low resilience of fisherfolk to environmental and market shocks.

The initial phase resulted in the creation of a Strategic Action Programme (SAP), serving as both the political commitment and the institutional plan to tackle these issues through regional collective efforts.

BOBLME Phase II: Sustainable Management and Ecosystem Health

The second phase of the BOBLME Project (2023-2028), known as "Sustainable management of fisheries, marine living resources and their habitats in the Bay of Bengal region for the benefit of coastal states and communities," is now underway. A consortium of partners- including BOBP-IGO (covering South Asia), IUCN, and SEAFDEC- is executing this phase. It is organised around five main components aimed at implementing the SAP.

- **Component 1:** Sustainable Management of Fisheries: This component directly supports the EAFM initiatives championed by the BOBP-IGO, focusing on securing shared fish stocks like Hilsa, Mackerel, and Sharks, through regional dialogues, data sharing, and harmonized management plans.
- **Component 2:** Restoration and Conservation of Critical Marine Habitats and Biodiversity: This addresses the environmental integrity of the ecosystem, focusing on the protection and restoration of vital habitats that serve as spawning and feeding grounds for marine life.
- **Component 3:** Management of Coastal and Marine Pollution: This component is critical for improving overall ecosystem health by tackling pollution sources, including the increasingly alarming problem of plastic litter and microplastics.
- **Component 4:** Improved Livelihoods and Enhanced

  Resilience: This is the human dimension, aiming to diversify livelihoods, strengthen community participation in management (co-management), and build the resilience of vulnerable coastal populations to climate change and resource scarcity.
- **Component 5:** Regional Mechanism for Planning, Coordination, and Monitoring: This ensures the long-term institutional sustainability of the cooperative framework beyond the life of the project.

The BOBLME Project likely represents the most prominent example of the BOBP-IGO's role, turning it into the main operational body for the region's largest marine ecosystem management effort and integrating holistic, science-based conservation principles into national policies.

Other Initiatives of BOBP-IGO

Exchange of Knowledge: Joint Research and Harmonisation

BIMReN (BIMSTEC-India Marine Research Network) serves as a regional platform led by BOBP-IGO, aiming to enhance research, training, and science–policy collaboration focused on the Blue Economy across the Bay of Bengal. Building upon India's SAGAR initiative, "Neighbourhood First" policy, and the Kochi Declaration, BIMReN acknowledges the shared nature of fisheries and marine ecosystems, striving to strengthen joint efforts to combat climate change, overfishing, IUU fishing, habitat degradation, and improve fisher safety.

The initiative is built on three main pillars: (1) Split-Site Doctoral Fellowships that send PhD candidates from BIMSTEC countries, as well as eligible nationals abroad, to top Indian universities and labs for their research; (2) Small "Twinning" Research Grants that facilitate faculty exchange and collaboration between Indian institutions and partner institutes across BIMSTEC; and (3) a biennial Blue Economy Conference designed to share results, foster long-term networks, and connect researchers with policymakers.

Curbing IUU Fishing

The BOBP-IGO Regional Action Plan to Prevent, Deter, and Eliminate IUU Fishing (BOB RPOA-IUU) is a voluntary, seven-year initiative (2024–2030) for Bangladesh, India, Maldives, and Sri Lanka. It aims to reduce IUU fishing within their EEZs and nearby ABNJ by combining national sovereignty with regional cooperation and stakeholder involvement. Based on the FAO Code of Conduct, IPOA-IUU, VG-SSF, and UNCLOS, the plan includes key actions such as appointing national focal points, developing and reviewing NPOA-IUU regularly, strengthening and harmonizing MCS activities (joint patrols, inspections, observer programs), creating a regional vessel record compatible with FAO's Global Record, enforcing vessel marking/IMO numbers and gear standards, aligning port State measures and SOPs with PSMA, compiling transparent regional IUU vessel lists, improving product classification and post-harvest handling, implementing risk-based catch documentation, and establishing regional information-sharing and risk assessment systems. Additionally, the plan advocates for regular assessments of IUU challenges, technical support to States, and targeted capacity building to address implementation gaps over time.

Safety of Fishers at Sea

BOBSAFE (Bay of Bengal Programme's plan for enhanced safety, decent work, and social protection in fisheries) is a regional strategy running from 2023 to 2032 for Bangladesh, India, Maldives, and Sri Lanka. It aims to reduce fishing fatalities, improve safety standards, and expand social protection in marine fisheries. The plan introduces standardized accident and fatality reporting with public transparency to enable countries to learn from root causes. It enhances vessel safety through licensed boatyards, approved small-vessel designs, inspections, and rules on stability and loading, aligning with IMO/FAO/ILO standards and working towards Cape Town Agreement compliance. At the crew level, it requires lifesaving equipment, reliable communication tools, emergency drills, basic safety and navigation training, minimum living conditions, and regular health checks according to ILO C188. It encourages decent work by clarifying labour terms, establishing hours and rest standards, grievance mechanisms, and gender-responsive policies that support women throughout the value chain. BOBSAFE integrates safety and decent work policies into fisheries governance and monitoring, promotes inter-agency coordination, and invests in training centres, curricula, and regional exchanges, with clear indicators and annual progress reviews.

Knowledge Transfer and Capacity Development

The BOBP-IGO serves as a regional hub for knowledge and capacity building, integrating science and best practices into national and transboundary fisheries governance. Its key training initiatives, which cover the FAO Code of Conduct for Responsible Fisheries (CCRF), Ecosystem Approach to Fisheries Management (EAFM), and regional fisheries regulations, aim to support junior and mid-level officials, researchers, and community leaders in enhancing daily management. It also facilitates the sharing of effective strategies across borders by organizing experience-sharing visits to promote replication and expansion. Simultaneously, BOBP offers policy and legal guidance to assist members in interpreting and implementing complex agreements like the new Biodiversity Beyond National Jurisdiction (BBNJ) Treaty, and in aligning national biodiversity strategies with global developments.

Conclusion and Future Outlook

Over more than forty years, the Bay of Bengal Programme has developed into a vital Inter-Governmental Organisation. It has shifted from simply transferring technology to becoming a sophisticated regional advisory body and the operational backbone for one of the world's largest ecosystem management initiatives. The Bay of Bengal continues to face significant challenges, including a rapidly expanding population, a worsening climate crisis, and ongoing unsustainable fishing practices. Nevertheless, the BOBP-IGO employs an evidence-based, ecosystem-focused approach and maintains a unique structure that promotes regional cooperation. Its future strategy involves strengthening the integration of environmental and fisheries management, utilising innovative tools like Ocean Accounting and Marine Spatial Planning, and remaining a key think tank and catalyst. This ensures the long-term sustainability and prosperity of the' Blue Economy" for the millions dependent on this vibrant yet fragile Bay of Bengal Large Marine Ecosystem.

Lost at Sea: A Museum's Call to the Deep

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"After almost 100 years on the planet, I now understand the most important place on Earth is not on land, but at sea." — Sir David Attenborough

Oceans on the Edge

The oceans are not merely the planet's backdrop. They are its bloodstream — regulating temperature, nurturing biodiversity, and sustaining life in every known form. Nearly half of humanity, about 44%, lives within 150 kilometers of the sea. The oceans generate more than half the oxygen we breathe, carry 80% of global trade, and provide food security to over three billion people. Yet, they are existing on the edge today. At the Birla Industrial and Technological Museum (BITM), Kolkata, a unit of the National Council of Science Museums (NCSM), Ministry of Culture, Government of India, this edge — scientific, ecological, and moral — became the starting point for a new curatorial journey. The gallery "Lost at Sea", conceptualized and developed by BITM, will be inaugurated on 14 November 2025, India's Children's Day. It is both an exposition and an appeal — a space where visitors confront the reality of marine crisis and rediscover the ocean as a living, breathing entity. Since the 1970s, the seas have absorbed 90% of all human-induced global warming. They are hotter, more acidic, and less hospitable than ever before. Rising sea levels, coral bleaching, and the silent disappearance of species all mark an ocean under siege. Humanity is taking from the seas far more than it gives back, eroding the very systems that sustain life on Earth. Museums today cannot merely preserve the past. They must interpret the present and provoke the future. Lost at Sea was born of that conviction — to translate ecological urgency into public experience, turning scientific data into shared emotion and informed action.

Curating a Crisis

"The awful status of these species should shock us and engage us for urgent action." — Prof. Amanda Vincent, Chair, IUCN Marine Conservation Committee

In museological practice, interpretation is not just communication; it is transformation. The curator's task is to bridge facts and feelings — to make data tangible and empathy measurable. Lost at Sea adopts a two-phase interpretive framework:

Phase I: "Sea More" — exploring the oceans as a resource of life, economy, and imagination. Phase II: "Existing Amidst Extinction" — confronting the vulnerability of marine ecosystems and species.

Together, the two phases form a dialogue between use and loss, knowledge and responsibility. By combining immersive technology, environmental science, and artistic storytelling, the gallery creates an experience that is as sensory as it is cerebral.

The philosophy guiding it is simple: people protect what they understand — and they understand what they experience.

Phase I – Sea More (From Utility to Understanding)

The first phase, inaugurated earlier in 2025, invites visitors to "sea more" — to look beyond the surface. It opens with The Lantern of Life, a revolving light installation projecting silhouettes of endangered species across the walls. Each slow rotation becomes a reminder that these outlines are fading — and with them, the living stories they represent.

Di-Gyo-Taku: From Line to Life

At the heart of this section lies Di-Gyo-Taku, a digital revival of the 19th-century Japanese practice of fish-printing. In the past, fishermen pressed real fish onto rice paper to preserve their likeness. Our interactive exhibit invites visitors to select and release digital fish into a virtual ocean, where they swim naturally in projected waters. It is a bridge between art and science, documentation and imagination — an homage to both history and ecology.

What's the Ocean Worth?

Few realize the ocean's immense economic power. Through striking infographics and 3D data representations, What's the Ocean Worth? demonstrates that if the sea were a country, it would rank as the eighth-largest economy in the world, generating USD 2.6 trillion in annual value and sustaining over 100 million jobs.

"Most of the Earth's biosphere — 99% of all liveable space — is under water." — Prof. Jon Paul Rodríguez, IUCN Species Survival Commission

Here, statistics acquire physical presence, enabling visitors to "feel" scale through spatial design. The exhibit translates abstract economic data into a tangible narrative — that the ocean's health is our shared wealth.

Walk on the Beach

An AR-enabled floor transforms the gallery into a living shoreline. As visitors walk, messages about extinction emerge briefly underfoot — fleeting words that fade with every step.

Discovering the Deep

Through interactive consoles, visitors encounter the enigmatic life of the deep sea — glowing fish, transparent shrimp, and pressure-defying jellyfish. "No matter how deep or dark, our oceans are alive," reads a quiet inscription.

Phase II – Existing Amidst Extinction (Witness to Loss)

Ready for unveiling on 14 November 2025, the second phase turns from curiosity to conscience. While Sea More celebrates vitality, Existing Amidst Extinction confronts disappearance.

Marine Megafauna

Here, life appears on an extraordinary scale — a life-size blue-whale calf surrounded by data on whales, walruses, crabs, and turtles. Visitors learn how metabolic rate, habitat depth, and body size define longevity.

Extinct Marine Species Wall

The AR-enabled Extinct Species Wall resurrects lost species — the Steller's sea cow, the Great Auk, the Caribbean monk seal, the Java stingaree — creatures that once defined ecosystems, now reduced to memory. Scanning a code brings them briefly "alive" in augmented reality. They appear, shimmer, and fade.

Living Lights

In near darkness, visitors enter the Living Lights zone — glowing acrylic panels reveal how luciferin and luciferase create nature's own light show. Bioluminescence, the exhibit teaches, is communication, defense, and attraction rolled into one.

Coral Conservation

Coral reefs, covering less than 0.1% of the ocean floor yet hosting a quarter of marine life, are vanishing rapidly. Through an interactive rotary system, visitors manipulate environmental variables — temperature, pollution, sunlight, and tides — to "bleach" or "revive" corals.

Museums as Ethical Witnesses

The National Council of Science Museums operates on the belief that science communication is public service. Our museums across India are civic classrooms — places where visitors meet science not as abstraction, but as lived culture.

Lost at Sea embodies that mission. It is not a gallery about the ocean; it is a gallery for the ocean. Its approach reflects affective museology — where emotion catalyzes comprehension. Every exhibit converts complex marine science into human story.

The Blue Thread – Science, Art and Imagination

Running through the gallery is a unifying idea — the Blue Thread that ties ecology, economy, and empathy together. From the poetic interactivity of Di-Gyo-Taku to the data rich infographics of Ocean Worth, each component speaks a different dialect of the same ideal, coexistence.

From Observation to Action

"It is vital that we manage fisheries properly, constrain climate change and reverse habitat degradation." — Prof. Amanda Vincent

Lost at Sea concludes with a corridor of reflection, its final question glowing softly above an undulating projection of waves: "If the oceans die, what will remain alive?"

For NCSM, this exhibition is not an endpoint but a beginning.

Through outreach programmes, teacher workshops, and school group visits, BITM will extend the gallery's learning beyond its walls.

Conclusion: A Living Laboratory

Museums have long been called "archives of the past." At NCSM, we call them laboratories for the future. Lost at Sea is one such laboratory — where science, art, and empathy converge to cultivate ecological literacy. The ocean's story is not remote. It is written in every monsoon, every fish market, every breath we take. The sea is our shared inheritance and our shared responsibility.

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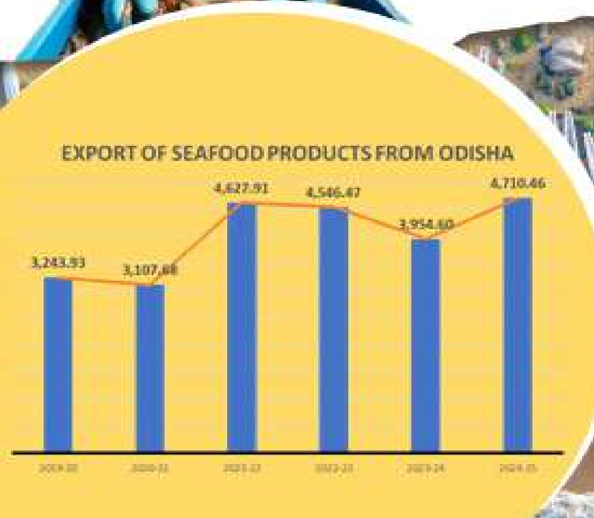
Resource Profile Odisha

4th Position in National Ranking Fish Production [2021-22]

- Coastline: 576 Km
- Continental shelf: 24,000 sq. Km
- Brackish water resource: 4.18 Lakh Ha.
- Cultivable brackish water area: 33,000 Ha.
- Estuary: 2.98 lakh Ha.
- Backwater: 8,100 Ha.
- Chilika Lake: 79,000 Ha.
- Inland water resource: 7.04 Lakh Ha.



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