Marine living resources – a blue future

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India's vast exclusive economic zone (EEZ) with its rich bounty of living and non-living resources, offers a great opportunity to expand its economy and food security, and could enable sustainable development and create resilient jobs. Marine fisheries, mariculture and marine bioprospecting are significant sectors which could act as the next big drivers of the GDP and public welfare. Marine biodiversity documentation sporadically requires innovative techniques using genomics in combination with underwater imagery to cover the full spectrum of marine living resources. Deep waters beyond 500 m depth are not optimally exploited and offer immense scope for commercial exploitation. The mariculture sector, despite the wide array of candidate species, is still in its infancy and requires the use of genetic engineering to develop breeds suitable for the mariculture systems. Employing new analytical technologies and a wide range of 'multiomics' tools can enhance the bioprospecting of numerous marine living resources, which have the potential to unravel hundreds of new compounds for human well-being. Ascertaining the continuity of the blue economy demands judicious management of oceanic resources through innovative and sustainable practices.

Keywords: Blue economy, biodiversity, mariculture, marine bioprospecting, marine fisheries.

Introduction

OCEANS cover 70% of the Earth's surface, provide food and livelihood for a large part of the global population, and facilitate 80% of the global trade, a key resource for economic development and prosperity. According to a WWF report, the oceans have an economic value equivalent to the world's seventh largest economy in terms of gross domestic product (GDP), exceeding US$ 25 trillion per year[1]. India with 12 major and 187 non-major ports handles about 1400 million tonnes of cargo annually (i.e. 95% of the country's trade by volume). India's exclusive economic zone (EEZ) extending over 2.37 million km^2, has a bounty of living (18,000 known species, i.e. 7% of global marine biodiversity)[2] and non-living resources such as oil and gas. Its coastal economy spread along 7517 km of the coastline spanning nine coastal states and 1382 islands supports over 4 million fisherfolk and coastal communities for their livelihood and culture[3]. The ocean surrounding India thus offers a great opportunity to expand its economy, food security and creation of jobs. Industries and activities reliant on the oceans, such as fishing, tourism, ports and shipping have become a synonym for the blue economy[4], and are crucial for India's future growth and prosperity. Considering the paramount significance of oceans as a source of economic growth as well as a reservoir of living and non-living resources, the Government of India (GoI) drafted a Blue Economy Policy which aims to unlock the country's potential for economic growth and welfare by harnessing its vast maritime interests[5]. Primary industries which can fuel the blue economy encompass a wide range of sectors, involving living (fisheries, aquaculture and bioprospecting) and non-living components (shipping, tourism, and offshore oil and gas exploration). The blue economy could be the next big driver of GDP and welfare if managed with sustainability and social justice in consideration[6,7].

This article addresses the significance of marine living resources in the Indian seas and their potential for economic growth and other benefits, particularly in the context of biodiversity, fisheries, mariculture and biotechnological prospects. It also examines the challenges and constraints for the sustainability of marine living resources.

The Indian Ocean – a region with rich biodiversity

The Indian Ocean covers 27.2 million square miles, which is ~20% of the total ocean surface area. Efforts towards documenting marine biodiversity in the Indian Ocean, including the Indian EEZ commenced with the description of species by Linnaeus[8]. Dedicated expeditions, namely Novara (1850)[9], Royal Indian Marine Survey Ship 'Investigator' (1884–1913)[10], Valdivia (1898–99)[11], John Murray Expedition (1933–34)[12], Galathea (1950–52)[13], Xarifa (1957–58)[14] and the first International Indian Ocean Expedition (IIOE; 1959–65)[15] extensively surveyed the northern Indian Ocean. Surveys in the Lakshadweep Archipelago revealed coral reef-associated fauna of the region[16]. Most of those surveys concentrated their efforts towards documenting coastal marine biodiversity owing to easy accessibility and favourable bathymetry. Despite these studies, documentation of biodiversity remained patchy in terms of geographic coverage, thereby necessitating comprehensive surveys across the region for understanding discernible

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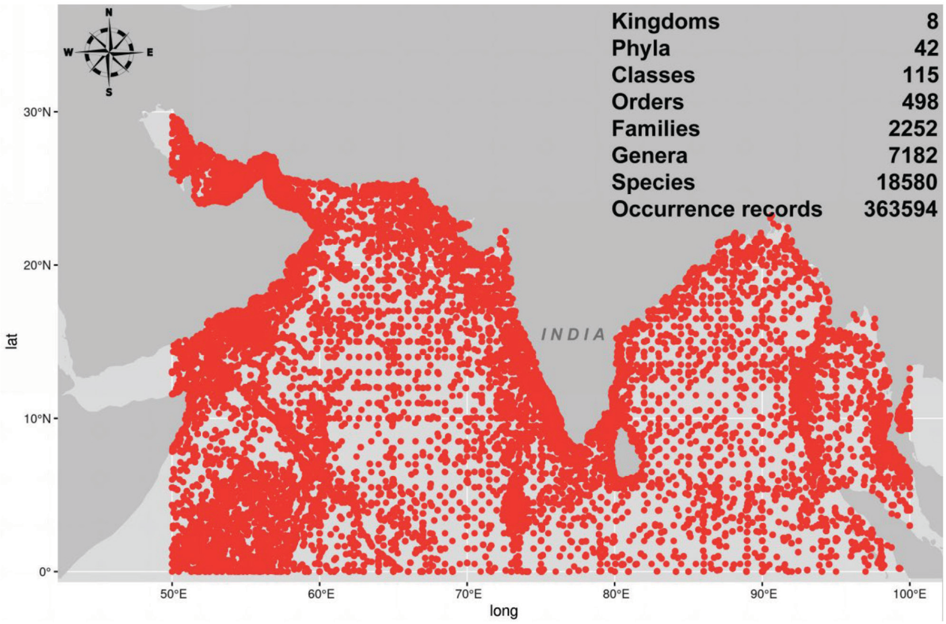

Figure 1. Spatial coverage and taxonomic classification of the occurrence records of marine organisms in the northern Indian Ocean based on primary and secondary data (source: https://indobis.org/).

changes in biodiversity[17]. Given this, the Ministry of Earth Sciences (MoES) of India, located in New Delhi, implemented a national programme on marine living resources (MLRP) through the Centre for Marine Living Resources and Ecology (CMLRE) in Kochi, Kerala during the Ninth plan period (1998). Since then, exploratory surveys on-board the Fisheries and Oceanographic Research Vessel *Sagar Sampada* have yielded moderately large faunal collections, which have been taxonomically identified, described, inventoried and archived in reference museum collections (Bhavasagar). After the first IIOE during 1960–1965, MLRP spearheaded extensive biological explorations through research programmes, namely Integrated Taxonomic Information System, Deep-Sea and Distant Water Fishery, Monitoring and Modelling of Marine Ecosystem and Resource Exploration and Inventorization System resulting in significant inventory of marine species in the region[18]. In 2018, the Ocean – Services, Modelling, Application, Resources, and Technology (O-SMART) scheme was formulated by MoES, GoI, to promote research and capacity building in marine biodiversity and ecology. In 2019, GoI announced the Vision of New India by 2030 highlighting blue economy as one of the ten core dimensions of growth[5], leading to the launch of an ambitious Deep Ocean Mission (DOM) to support the blue economy initiatives of the nation.

Seas around India harbour an incredible diversity of marine life, ranging from microscopic plankton to giant whales[2]. The major groups of organisms are as follows:

- Plankton constitute the base of the marine food chain and play a crucial role in oxygen production.
- Seaweeds and algae provide food and shelter for numerous marine species and contribute to carbon sequestration.
- Seagrasses and mangroves provide habitat, shelter and food for numerous organisms.
- Invertebrates such as sponges, corals, worms, molluscs, crustaceans and echinoderms form an integral part of the trophic web in marine ecosystems.
- Fishes (over 2500 species) support large-scale fisheries and provide livelihood for the coastal communities.
- Marine mammals (whales, dolphins, porpoises and dugongs) contribute to the balance of marine ecosystems and attract ecotourism.

India being a party to several conventions dealing with conservation and sustainable use of biological diversity, it became mandatory to document the marine resources. Accordingly, CMLRE joined the Ocean Biogeographic Information System (OBIS), an international digital marine biodiversity dissemination platform, to provide open access to data on marine biodiversity. Accordingly, details of 363,594 occurrence records of 18,580 marine species belonging to 8 kingdoms, 42 phyla, 115 classes, 498 orders, 2252 families and 7182 genera have been disseminated through the regional node of OBIS – IndOBIS portal[19] (Figure 1).

The diverse life forms in the ocean and their ecological interactions are vital for the health and functioning of marine ecosystems, which provide us and the planet with many benefits and services such as food and nutrition security for coastal communities, regulation of climate and carbon sequestration, protection of coastlines from erosion and storms by forming natural barriers like coral reefs and mangroves, cultural, spiritual and recreational value for humans, opportunities for innovation and discovery of new resources (food, medicine, biotechnology, etc.), fostering scientific research and innovation by providing a wealth of knowledge, and potential for discoveries and technologies, etc.

Moreover, marine biodiversity drives the blue economy through various economic activities as listed below:

- Marine capture fisheries and mariculture which depend on genetic diversity, population structure and ecosystem balance of marine resources.
- Biotechnology and pharmaceuticals which utilize the unique and diverse biological and chemical compounds and processes of marine organisms for manufacturing drugs, biofuels, cosmetics and enzymes.
- Marine tourism with a global worth of USD 3.0 trillion in 2022 (ref. 20), based on aesthetic, cultural and recreational values of marine biodiversity, and conservation and restoration of marine ecosystems.

To achieve a sustainable blue economy, we need to understand the diversity of marine life. Traditional methods of studying ocean biodiversity are often limited and costly, as they cannot capture the complete diversity of species and their interactions. Therefore, new genetic technologies, such as Sanger sequencing and Next generation sequencing (NGS), have been developed to identify and characterize different species and their interactions using environmental DNA (eDNA). eDNA is the genetic material that organisms leave behind in their surroundings, such as water, soil or air. eDNA can provide information on the presence, abundance and activity of marine organisms, as well as their responses to environmental changes[21]. International programmes such as Earth BioGenome Project (genomes of all of the Earth's eukaryotic biodiversity), Earth Microbiome Project (microbial life on this planet), Sponge Microbiome Project (sponge-associated microbial communities) and Vertebrate Genomes Project (complete reference genomes of all vertebrate species) have made good progress in understanding the biotic communities by adopting NGS. Unfortunately, the lack of such reference data from the Indian Ocean makes it difficult to map biodiversity extensively. Hence, it is necessary to build capacity and mobilize resources to generate extensive data by combining genomic approaches with underwater image analysis using machine learning and artificial intelligence[22].

Marine fisheries

After the declaration of EEZ in 1976, India is able to harness living resources from an estimated area of 2.37 million km^2 spread over 0.75 million km^2 (31.6% of the total) on the west coast, 0.56 million km^2 (23.6%) on the east coast, 0.40 million km^2 around the Lakshadweep archipelago (16.9%), and 0.66 million km^2 (27.8%) around Andaman and Nicobar Islands. The country's marine fishing industry has grown rapidly with a recorded fish production of 3.49 million tonnes (2022), with heavy dependence on capture fishing of 1062 fish and shellfish taxa[23]. Assessment of stocks of 70 species (49 finfishes and 21 shellfishes) suggested that 86.7% of the stocks is being fished within biologically sustainable levels[24]. India's revised annual Potential Yield Estimate (PYE 2018) is 5.31 million metric tonnes[25]. However, the fishing industry faces challenges, including (i) fragmentation – small fishermen lacking access to modern technology rendering them less competitive than larger players in the market; (ii) low financial investment resulting in low margins for fishermen, and (iii) overfishing due to poor regulation which threatens the sustainability of the industry and marine ecosystem. Nevertheless, initiatives such as the Pradhan Mantri Matsya Sampada Yojana have been launched to achieve the Blue Revolution through sustainable and responsible development of fisheries in India, thus enabling the growth of industry to a great extent[26]. However, private sector investment is needed to improve its productivity, profitability and resilience[27].

An expert committee constituted for a comprehensive review of the deep-sea fishing policy and guidelines indicated that production from near-shore waters of the Indian EEZ has stabilized with minimal scope for further increase[27]. This places an urgent need for sustainable harvest of resources in the near-shore waters and deep sea (Figure 2).

Waters beyond 500 m depth are not optimally exploited. A recent estimate indicated harvestable potential of 3.3 million metric tonnes of fish in the deeper parts of the EEZ (200–2000 m depth, pers. commun.). Except for the marginal harvest of some crustaceans, most deep-sea are resources have remained under-harvested or unharvested. More than 250 different deep-sea fishes, mostly belonging to the orders Perciformes, Ophiidiformes and Gadiformes, have the potential for sustainable harvest (pers. commun.).

Deep-sea fishery resources in the Indian EEZ, primarily comprising fishes and crustaceans, are estimated at 2500 kg km^{-2} at 800–1500 m depth in the Arabian Sea, 1600 kg km^{-2} at 600–1100 m depth in the Bay of Bengal and 1400 kg km^{-2} at 200–600 m depth in the Andaman waters (pers. commun.). Potential fishing grounds for deep-sea prawns were identified along the SW and NW coasts of India and Andaman Sea at a depth 200–400 m, and for demersal fishes, namely *Priacanthus* spp., *Bembrops* spp. and *Chlorophthalmus agassizi* along the SW coast at 200–400 m depth (pers. commun.). The total abundance of mesopelagic fishes in the northern and western Arabian Sea was estimated at 100 million tonnes[28], dominated by 46 species of myctophids, at depths exceeding 150 m (ref. 29). This accounts for about 75% of the total global catch of small mesopelagic fishes[30]. These fishes possess high-quality polyunsaturated fatty acids, and are therefore ideal for

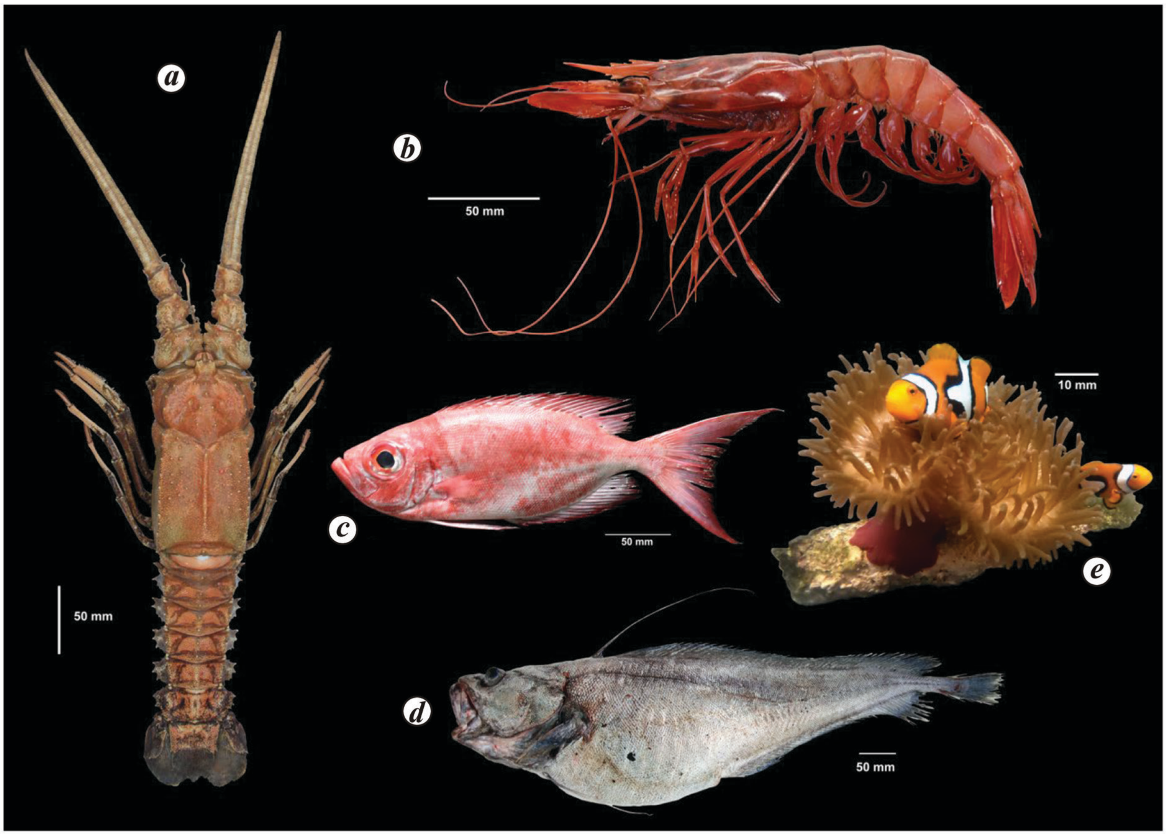

Figure 2. Commercially exploited and potentially important marine species in the Indian seas. ***a***, Spear lobster *Linuparus somniosus*; ***b***, deep-water red shrimp *Aristeus alcocki*; ***c***, moon-tail bullseye *Priacanthus hamrur*; ***d***, deep-sea cod, *Lepidion inosimae*; ***e***, orange clownfish *Amphiprion percula*.

human consumption and aquaculture feeds with appropriate post-harvest processing. Other resources, including straddling and migratory fishes such as squids, tunas and billfishes have huge commercial potential in areas beyond national jurisdictions, which are harvestable sustainably by adhering to various conventions and treaties. However, biological studies of deep-sea fishes revealed that they exhibit slow growth rate, high longevity and low fecundity[31]. Hence, extreme caution needs to be exercised while harnessing deep-sea fishery resources. The technology needed for accessing, harvesting and post-harvesting the deep-sea resources should be made affordable to the fishing communities and industries.

Although deep-sea resource mapping based on exploratory surveys has facilitated the generation of immense information on the diverse composition, assemblage patterns and habitat ecology of some of the deep-sea resources, it is recommended that the process should be continuous and consistent.

Mariculture

Since capture fisheries are not expected to grow as required, an emphasis is being placed on aquaculture to provide increasing quantities of aquatic products. Out of an expected additional production of 10 million tonnes of fish needed by 2025, about 4–5 million metric tonnes could be achieved from mariculture[32]. Diverse groups of finfishes (cobia, silver pompano, Indian pompano, Asian sea bass and grouper), bivalves (green mussel, edible oyster and clam), crustaceans (swimmer crab, tiger prawn and spiny lobsters) and seaweeds are candidate species for which mariculture technologies have been perfected and standardized[33]. However, commercialized mariculture in the Indian Ocean is still in a nascent stage and will go a long way in realizing the blue economy potential in India[32].

Marine ornamental fish production is an alternative opportunity to augment the revenue. Over 40 million marine organisms representing 1471 species are traded annually with a value exceeding USD 1.0 billion (ref. 34). A long-term sustainable option for developing marine ornamental fish trade is through hatchery production. The hatchery technology for breeding species of clown and damselfishes has been perfected in India by CMLRE. However, further research is needed to develop technologies for more species and upscaling the operations[35]. Possibilities also exist for miniaturizing traditional large aquariums, where changing water affects quality and temperature, thereby impacting fish life. Therefore, a miniaturized system maintained by artificial seawater with marine ornamental fishes is a promising alternative option (pers. commun.).

Marine biotechnology can be used to improve mariculture in several ways; for example, bacteria-based probiotics can help improve the health and growth of shrimp[36]. Gene editing could enable development of new, disease-resistant mariculture breeds with better feed conversion efficiency and rapid growth[37], which could further improve the sustainability and profitability of mariculture. Genetic engineering of fishes allows rapid growth and survival[38], and could be extended to several more species[39]. However, issues regarding public preference for genetically modified seafood, legal considerations and safety concerns for the environment persist. Advances in marine biotechnology have enabled the development of new vaccines to protect fishes from diseases, such as salmonid alphavirus and salmon anemia virus[40]. Genetically modified algae can be engineered to produce higher amounts of omega-3 fatty acids, or grow faster and more efficiently, leading to reduced dependence on wild-caught fishmeal and other unsustainable feed ingredients in aquaculture[41].

Marine bioprospecting

Marine biotechnology focuses on developing products and processes using marine organisms, their genes and metabolites to make medicinal, agricultural, industrial and environmental useful/protection products. It also enables the advancement of aquaculture and seafood safety, bioremediation and biofuels[42]. India has a growing marine biotechnology sector, with active research and development by MoES, GoI, Department of Biotechnology (DBT), the Council of Scientific & Industrial Research (CSIR), the Indian Council of Agricultural Research (ICAR), and various universities. The country is investing in this field with a focus on developing disease diagnostics and vaccines, bioactives, transgenics to improve fish and shellfish farming, bioprospecting, biofilms and biofouling, and functional genomics. The development of marine biotechnology is being supported through Biotechnology Parks and Incubation Centres.

The global marine biotechnology market is expected to grow by 4.2%, reaching a projected value of US$ 5.86 billion by 2028 (ref. 43). Marine biotechnology products from the Indian Ocean have the potential to generate a trillion-dollar business and an employment generator boosting economic growth.

Genes of diverse organisms produce secondary metabolites (e.g. peptides, sterols, phenols, terpenoids and alkaloids) with diverse functions beneficial for health, cosmetics and other industries. Marine bioprospecting is a subset of marine biotechnology involving systematic search for new and useful biological resources from the marine environment, including drugs, enzymes, new materials and other products that could benefit society. A classic example of marine resources for human benefit is the discovery of green fluorescent proteins used for detection, imaging, biosensing and bioreporting[44,45], and other biochemicals for bioremediation[46], protein tagging[47], antibiotics[48] and plastic degradation[49].

Marine drugs are derived from the bioactive compounds of marine organisms. Globally, more than 30,000 marine natural products have been isolated and identified[50], of which only 21 have been approved as drugs in the United States and the European Union[51], largely for cancer treatment. Additionally, more than 200 compounds are in various phases of clinical trials[52], including halymeniaol[53] and fucoxanthin[54] from India.

Marine animals are also a source of cosmeceuticals and nutraceuticals (vitamins, carbohydrates, proteins and peptides, antioxidants and omega-3 fatty acids). Anti-inflammatory and anti-toxin creams have been produced from sessile metazoans[55] as well as symbiotic microbes[56]. Marine genes are also used to formulate a wide array of detergents, chemicals, pharmaceuticals, emulsifiers and stabilizers for food production[57]. Bioplastics extracted from seaweed polymers are used for manufacturing food packaging, bags, agriculture and horticulture, disposable housewares, medical devices, consumer electronics and automotives[58].

Although researchers have isolated thousands of compounds, the development of marine biotechnology products from marine resources of the Indian seas faces several challenges. These include paucity of skill, expertise and infrastructure in developing the products. Efforts should be focused on identifying new marine organisms with useful biomolecules, developing sustainable methods for harvesting and cultivating marine organisms, conducting preclinical and clinical trials, etc.

Conservation of marine biodiversity

Marine biodiversity refers to the variety of life found in the ocean, which is home to a vast and diverse collection of genetic material known as ‘ocean genome’. Possessing more genes implies having multiple options for evolution and survival. Thus, protecting the genetic diversity of ocean life from environmental threats is essential to maintain health and resilience to various challenges, and ensures that they continue to benefit future generations.

Natural (climate change) and anthropogenic (overfishing, coastal development, eutrophication, dredging, etc.) stress on marine life affect their population and loss of genetic diversity over time causing negative effects on growth, reproduction, resilience and survival with effects on their productivity and ecosystem services[59,60]. Thus, the protection and conservation of marine life should be imperative for blue economy activities.

The IUCN World Conservation Congress in 2016 recommended the goal of designating 30% of the ocean as ‘highly protected’ by 2030 to save adequate biodiversity, biomass and habitats[61]. Accomplishing such stiff targets requires quick action by policymakers to protect the ocean genome. Judicious management of the remaining 70% also is necessary to mitigate the harmful impacts on marine life.

It is noteworthy that only 7% of the ocean is legally protected in designated Marine Protected Areas (MPAs), with only 2% being fully or strongly protected[62]; only 0.003% of the Indian EEZ is designated as MPA. The MPA networks should include ecosystems offering high levels of genetic diversity, diverse habitats and depth ranges, where marine species can navigate and adapt[63]. Other conservation practices include managing fisheries sustainably, and reducing pollution from land-based sources and greenhouse gas emissions. India has undertaken several initiatives for the conservation of coastal and marine resources through the Wildlife Protection Act of India (1972), the National Committee on Mangroves, Wetlands and Coral Reefs, the Coastal Regulation Zone Notification, the Biological Diversity Act (2002), the Biological Diversity Rules (2004) and the guidelines thereof.

Several international frameworks and institutions, including the Convention on Biological Diversity, United Nations Convention on the Law of the Sea (UNCLOS), and World Intellectual Property Organization are facilitating the development of new modes of sharing the benefits and collaborating in the research of the biodiversity ocean genome. Various provisions in these instruments are being implemented by the Intergovernmental Oceanographic Commission, Global Ocean Observing System, and International Seabed Authority. On 19 June 2023, the Intergovernmental Conference on Marine Biodiversity of Areas Beyond Nation Jurisdiction adopted an Agreement, under UNCLOS (of which India is a part), to conserve and sustainably use marine biological diversity of areas beyond national jurisdictions. The Agreement includes binding and voluntary measures to promote benefit sharing, especially for developing countries.

Recommendations

Documentation and inventorying of marine fauna by adopting innovative methodologies and approaches such as eDNA metabarcoding, metagenomics, artificial intelligence and machine learning for image analyses, etc. should be implemented at a faster pace to track biodiversity and adopt effective quantitative and qualitative measures to preserve and enhance the marine living resources of the nation. This includes introduction of state-of-the-art technology for continuous resource mapping and assessment, sustainable harvesting and post-harvesting of deep-sea fishery resources, development of innovative tools for genetic improvement of mariculture species, enhancement of capacity in terms of skill, knowledge and infrastructure, etc.

Moreover, strict implementation of the provisions of national and international laws, conventions and treaties is necessary for the sustainable growth of marine living resources and their equitable sharing.

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