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Review

Sustainable blue economy: Opportunities and challenges

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The term 'blue economy', first introduced in 2010, is the sustainable use of ocean resources for economic growth, jobs, ocean health, and to improve livelihoods. However, a sustainable blue economy faces various challenges in the form of global warming, ocean acidification, and lack of knowledge about the ocean; for example, 95% of the sea is still unexplored, making it more important to understand the blue economy and implement it on a global scale. Other challenges include harmful algal blooms (HABs), invasive species, coral bleaching, and thermohaline circulation. This review discusses various aspects of the blue economy like food, value-added products, offshore energy, oxygen source, mining, fisheries, carbon sequestration, and cloud seeding. The future aspects of blue economy, like sustainability, effective policies, and reducing carbon footprints and microplastics are also explored here.

Keywords. Blue economy; marine; ocean; sustainability

1. Introduction

Oceans encompass 72% of the earth's surface; yet our knowledge about oceans, especially the deep sea, is limited. A famous aphorism says, 'We know more about the moon than our oceans'. Oceans contain 97% of the total water on earth, support economies in countries all over the globe, and are home to the planet's highly diverse ecosystems. Oceans discharge more than 90% of excess heat and absorb a third of carbon dioxide (CO_2) emissions from the atmosphere, controlling global temperature and stabilizing the climate. The health of the oceans is also critical for the survival and well-being of fragile communities like small island states, as well as high arctic and coastal communities (Landrigan *et al*. 2020).

The notion of a 'blue economy' was conceptualized in the United Nations Conference on Sustainable Development at Rio de Janeiro in 2012 in response to the growing importance of the ocean and marine industries to national economies. Since then, this concept has been widely discussed around the world. Numerous definitions exist for blue economy, or ocean economy. For instance, the report 'The blue economy: growth, opportunity and a sustainable ocean economy' in *The Economist* (Goddard 2015) states, 'A sustainable ocean economy emerges when economic activity is in balance with the long-term capacity of ocean ecosystems to support this activity and remain resilient and healthy'. One concept paper of the United Nations Development Programme (UNDP), 'The complexity of small island developing states' (Everest-Phillips 2014), defines it as 'a marine-based economic development that leads to improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities'.

The blue economy aims for a setback into an estimated USD 24 trillion in potential goods and services (such as mining, energy generation, maritime transport, tourism, capture fisheries, and aquaculture) obtained from the world's oceans and to strike an equilibrium between ocean industrialization and environmental protection (Cohen *et al*. 2019). Nowadays, this concept lines up with trade and economic deeds and surfaces

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from a requirement to mix sustainability and conservation in the management of the maritime domain (Smith-Godfrey 2016).

2. Goods and services (opportunities)

Various goods and services offered by marine ecosystems (figure 1) play a crucial role in human welfare. It has been estimated that around 3.1 billion people depend on the sea for 20% of their animal protein intake as seafood and ~500 million people are in ocean-related livelihoods. Oceans absorb almost a third of the CO_2 from human activities. Moreover, coral reefs and mangroves protect against extreme weather conditions such as floods and storms (OECD 2017).

2.1 *Goods*

2.1.1 *Food (fisheries and aquaculture):* The blue economy relies heavily on aquaculture and fisheries: 17% of global animal proteins are supplied by fisheries and aquaculture (Department AOotUNF 2000), supporting around 10–12% of the world's population. Currently, 3 billion people obtain 20% of their average per capita animal protein intake from fish (HLPE 2014). In developing countries, over 90% of livelihoods are directly dependent on fisheries and aquaculture, usually in small-scale operations (Ababouch and Fipi 2015). Although the production of fish from captured fisheries has stagnated at around 88 to 90 million tons over the years, the call for fish and fishery products has been rising. Since 1973, consumption has more than doubled. The growing demand has been regularly met through a steady growth in aquaculture production, expected at a median of 8% every year from 1970 to 2014, whereas the increase in global population is at an average of 1.6% per year. Consequently, the average annual contribution of food fish from aquaculture for human intake has expanded seven-fold (from 7% in 1970 to around 50% in 2014). This trend is expected to continue, with the contribution of aquaculture to the fish food supply expected to attain 65% by 2030 (Ababouch and Fipi 2015).

2.1.2 *Seaweed farming:* Over the last 50 years, the global macroalgae sector has grown exponentially. Between the years 2003 and 2012, it rose at an average yearly rate of 8.13% and 6.84% in quantity and monetary value, respectively. Around 23 million of macroalgae were produced by aquaculture (dry weight) in 2012, worth over USD 6 billion. About 83% of this biomass is used for human consumption, with the remaining used as animal feed additives, fertilizers, and increasingly, for biotechnological and medical

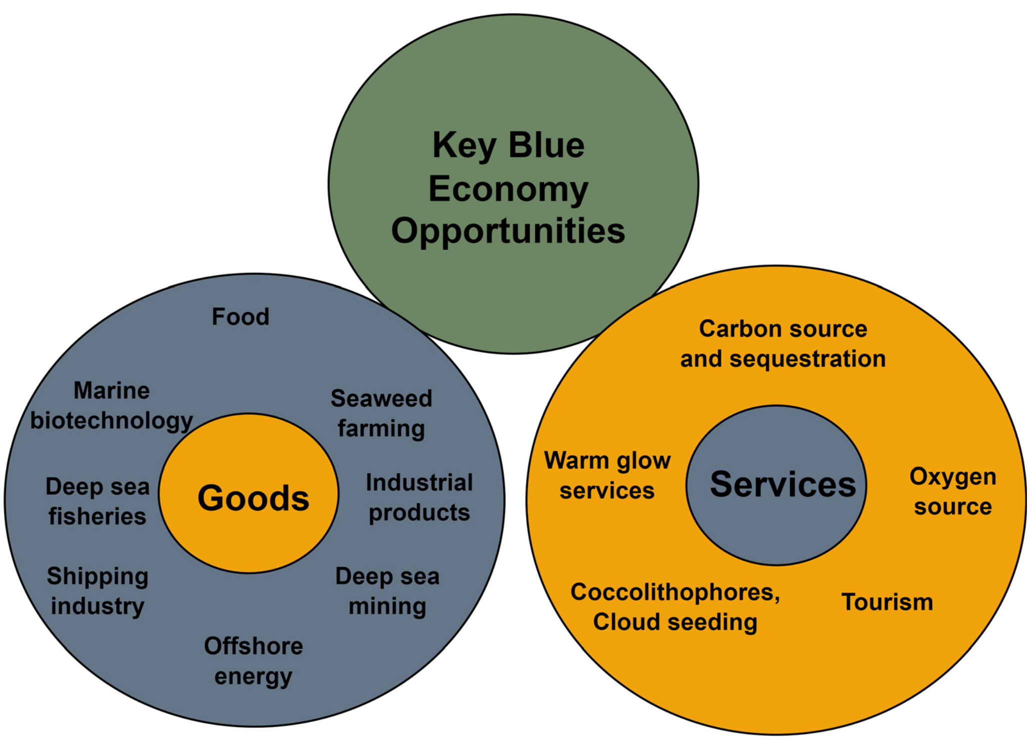

Figure 1. Various goods and services provided by oceans.

purposes. Furthermore, seaweeds are a source of biofuels that do not compete for resources with agriculture, as seaweeds do not need arable land, fertilizer, freshwater, herbicides, or pesticides. Thus, in several ways they are more environmentally sustainable than current biofuels made from land crops (Duarte *et al*. 2009, 2013, 2017).

2.1.3 *Value-added products: 2.1.3.1 Agar, alginate, and carrageenan* Alginate, agar and carrageenan are the most common polysaccharides derived from marine algae. Because of their capacity to generate highly viscous liquids and gels, hydrocolloids are widely employed in the food, pharmaceutical, biomedical, and biotechnology sectors (Ścieszka and Klewicka 2019). Use of agar in the food industry is approximately 90%, and the remaining 10% is used in bacteriology and biotechnology (Hernandez-Carmona *et al*. 2013). Carrageenan is used in aqueous gels, including fruit gels, jelly candies, juices, and marmalade. Pharmaceutical and meat industries (mainly obtained from *Eucheuma*) are the other fields of application of carrageenan (mainly obtained from *Eucheuma*) (Bixler and Porse 2011; Hernandez-Carmona *et al*. 2013).

All brown marine algae have alginate as part of their cell wall and intercellular matrix. It gives seaweed its elasticity and mechanical strength, allowing it to live in the sea. By adding certain divalent metals like Ca^{2+} to alginate, thermally stable gels can be made which are used in biomedicine, such as for drug delivery, wound healing, and tissue engineering applications (Lee and Mooney 2012). The most common commercial source of alginates is the marine brown algae of genera *Laminaria*, *Ascophyllum*, and *Lessonia*, whereas for agar production, red algae genera *Gelidium* and *Gracilaria* are used. For carrageenan manufacture, *Chondrus crispus*, also known as 'Irish moss', is the original raw material. However, carrageenan is made mainly from the algae *Kappaphycus alvarezii* and *Eucheuma denticulatum* (Ścieszka and Klewicka 2019)

2.1.3.2 Antifouling agents Many sessile marine species produce antifouling metabolites to compete for space and colonization. Some seaweed species also release antifouling chemicals that help prevent bacterial growth on their surfaces (Dobretsov and Qian 2002). Moreover, bacteria isolated from seaweed surfaces emit chemicals that repel other fouling bacteria, implying that they protect the seaweed from fouling by other organisms (Burgess *et al*. 2003). A team of scientists found that *Pseudoalteromonas tunicata* obtained from the surface of *Ulva australis* could produce certain biologically active compounds that could inhibit the growth of fouling organisms. *Bacillus, Exiguobacterium*, and *Vibrio* are other bacterial species associated with the surface of macroalgae that show antifouling activities (Dobretsov and Qian 2002; Burgess *et al*. 2003; Jain *et al*. 2013). Thus, these studies indicate that the chemicals used in antifouling coatings can be replaced with natural compounds derived from marine creatures.

2.1.3.3 Luminase Luminase is an enzyme that was discovered after extensive research on xylanase enzymes for use in bio-bleaching of pulp during paper manufacture with specified functions. Eventually, the luminase enzyme was generated from the sample obtained from an alkaline hot spring in Kamchatka, Russia's Uzon volcanic caldera. The luminase enzyme hydrolyzes the compound lignocellulose, providing the raw pulp's brown colour, thus allowing a 22% decrease in chlorine dioxide usage in the chemical bleaching stage, benefitting the environment by degrading harmful chemicals and reducing post-treatment costs. Developing luminase enzyme from sample collection to Environment Protection Agency (EPA) approval took 30 months, in contrast to the lengthy product development processes of pharmaceutical drugs. It was first presented in late 2004 and is currently being tested in several large-scale pulp mill studies around the United States (Mathur *et al*. 2005).

2.1.3.4 Feed and fertilizer Seaweed can be fed to a variety of animals. For instance, *Ulva lactuca* could be provided to male lambs up to 20% of diet, without impairing palatability. Low protein degradability (40%) and moderate energy digestibility (60%) make it ideal to use with low-protein/high-energy diets such as cereal grains (Arieli *et al*. 1993). For fish diets, algae are a natural substitute for soybean, offering nutritional and economic advantages, as soybean nutritional profiles indicate that this plant does not entirely match the fish's dietary requirements (Francis *et al*. 2001; Lovell 2003). Fish diets supplemented with seaweeds increase the growth, disease resistance, lipid metabolism, stress response, and physiological and carcass quality of several fish species (Soler-Vila *et al*. 2009; Güroy *et al*. 2011). Moreover, seaweeds are also used as poultry feed. The use of seaweeds in poultry feed helps to improve animal immunity, to reduce microbes in the digestive tract, and improve the quality of eggs (such as increased weight, shell thickness, yolk colour and reduced cholesterol in yolk) and meat (Wang *et al*. 2013a, b; Ali and Memon 2014; Makkar *et al*. 2016).

Overall 15 million metric tons of algal products are produced each year, with the majority being used as bio-fertilizers to improve plant growth and productivity. They can be utilized fresh, dried, or even composted, and their agricultural products have good tolerance, seed germination, plant growth, yield, stress tolerance, and resistance to disease infection or pests (Zodape 2001; Dineshkumar *et al*. 2017, 2018). The cyanobacterium *Tolypothrix tenius*, commonly utilized throughout Asia in rice fields as a nitrogen source, is grown in cultures and then applied to fields (Sampathkumar *et al*. 2019).

2.1.3.5 Ambergris Ambergris is a mysterious waxy material that has been known since the 9th century. It used to be a global economic commodity and was previously thought to be as valuable as incense. Its origin was a point of contention for a long time. Finally, in 1783, Sir Joseph Banks and Dr Franz-Xavier Schwediawer found that ambergris is a natural product of the sperm whale rather than something it ingests. In more recent periods, data from whale-catches backed up earlier reports that it only occurs in roughly 1 out of every 100 whales. The only known natural sources are sperm whales (and potentially pygmy and dwarf sperm whales). With synthetic chemical counterparts effectively replacing the natural ingredient in fragrance, ambergris is now essentially a rare chemical and biological curiosity (Rowland *et al*. 2019).

2.1.3.6 Carotenoids Around 750 naturally occurring carotenoids have been reported since Kuhn and Karrer originally elucidated the structure of β-carotene in 1930. More than 250 of these bioactive chemicals are marine-derived and exhibit structural variety, such as allenic carotenoids (e.g., fucoxanthin) and all acetylenic carotenoids (e.g., alloxanthin and tedaniaxanthin) derived from marine algae and animals (Maoka 2011). Marine carotenoids have potent antioxidant, healing, anti-inflammatory, and antiproliferative properties. They can be used for skin protection against the damaging effects of UV radiation or as a cosmeceutical/nutraceutical constituent to treat oxidative stress-related disorders (Berthon *et al*. 2017; Galasso *et al*. 2017).

2.1.3.7 Drugs from the sea One of the most fruitful disciplines of natural pharmaceutical research is marine natural products (MNPs), also known as 'blue gold' drug discovery (Montaser and Luesch 2011). According to a comparison study, MNPs have more chemical novelty than their terrestrial counterparts, and many of these are used regularly in clinical trials and pharmaceutical goods. At present, of the nine marine-derived drugs, six are approved for clinical therapy and one is an over-the-counter drug (OTC). Cytarabine, nelarabine, trabectedin, fludarabine phosphate, vidarabine (US discontinued), ziconotide, brentuximab vedotin, eribulin mesylate, and omega-3-acid ethyl esters are among the drugs accepted by the Food and Drug Administration (FDA) in the US Pharmacopeia and the European Agency for the Evaluation of Medicinal Products (EMA). However, it is anticipated that drugs of marine origin will continue to increase as 34 marine-derived drugs are at present in clinical trials (Mayer *et al*. 2023). Moreover, marine drugs under clinical trials, subdivided into three phases of clinical investigation are summarized in figure 2 (Cappello and Nieri 2021). These marine compounds have great potential as anticancer drugs, as many are being used in cancer therapeutics (Alves *et al*. 2018; Cappello and Nieri 2021).

2.1.3.8 Adhesives Natural sources of adhesives are found in marine mussels, barnacles, and oysters. They secrete proteinaceous substances or adhesives that allow them to adhere to sea beds or rocky surfaces (Foulon *et al*. 2018). 3,4-Dihydroxyphenylalanine (DOPA) is a catecholic functional group responsible for the adhesive properties of proteins produced by mussels (Yuvaraj *et al*. 2021). Recently, these properties have been applied to cure fractures, pain, and in dental therapies (Yuvaraj *et al*. 2021). 3,4-Dihydroxyphenyl-l-alanine acrylamide-polycaprolactone (L-DMA–PCL) hydrogels derived from mussels are used for sensing strains in biometrics and for healthcare monitoring (as strain sensors, which could convert different human motions into electrical signals) accurately due to their ease in sticking to human skin (Zhang *et al*. 2021). The adhesive material secreted by barnacles contains around 90% protein but has no peptidyl DOPA as do the mussels and tubeworm adhesives (Kamino 2013). Most adhesives used commercially are prepared from the proteins obtained from mussels; further research is required to discover the functions and structure of barnacle proteins.

2.1.4 *Marine biotechnology:* In the 1950s, for the manufacture of antiviral medications, nucleosides from the sponge *Tethya crypta* served as models. They were later significant for creating drugs such as azidothymidine (AZT) and acyclovir (used to delay the development of AIDS) used for patients infected with the human immunodeficiency virus (HIV). From

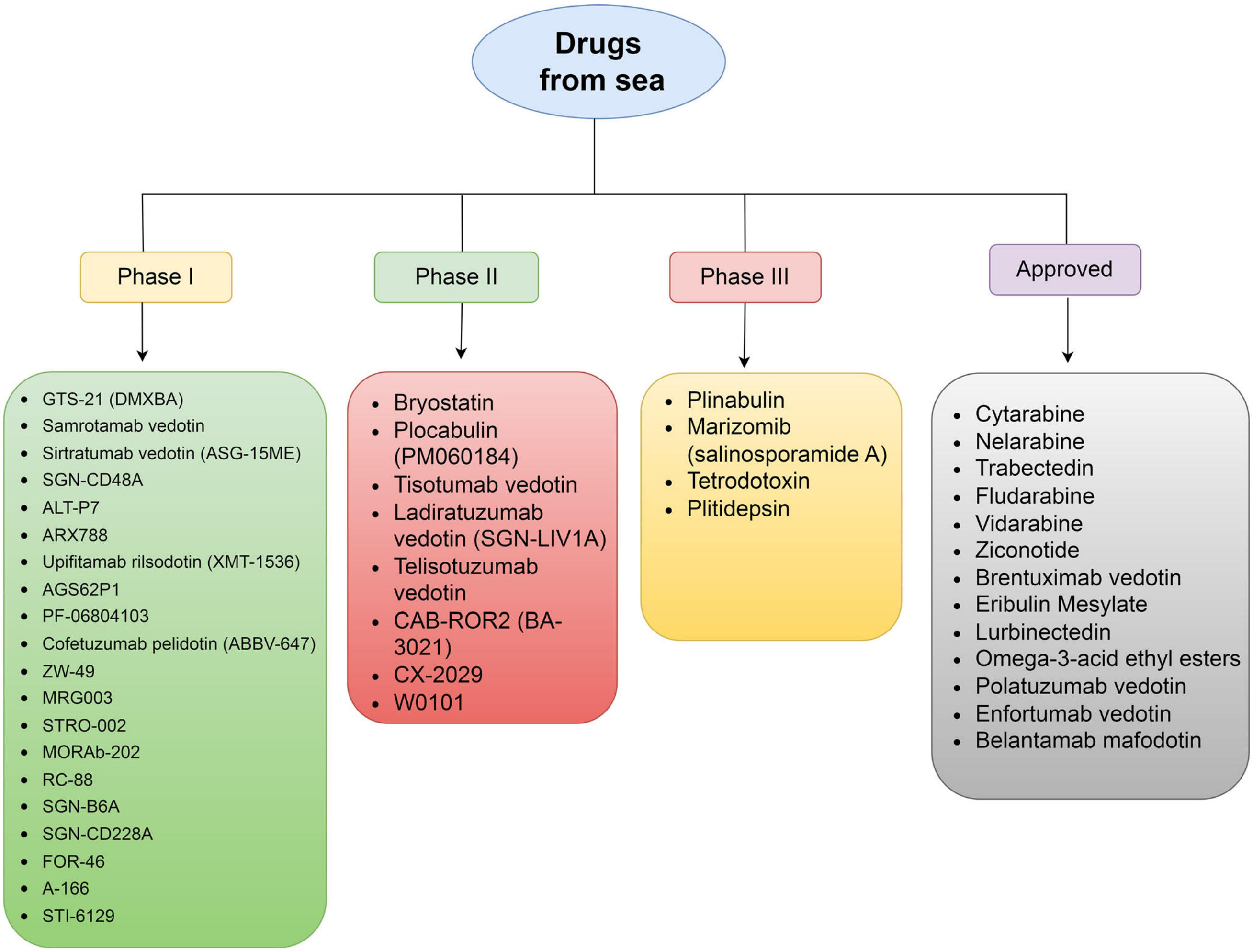

Figure 2. Flowchart showing the marine-derived drugs present in different phases of clinical trials (adapted from Alves *et al*. 2018; Cappello and Nieri 2021).

the marine bacteria *Pseudomonas bromoutilis*, the first marine antibiotic [2,3,4-tribromo-5(1-hydroxy, 2,4-dibromo phenyl) pyrrole] was discovered in the 1960s (Burkholder *et al*. 1966). However, of the 15,000 registered marine items, only two medications, Prialt R and Yondelis R are currently registered, with another 50 (roughly) in numerous stages of research. Therefore, more efficient use of genetic engineering could transform this situation by providing new enzymes for biotechnology, opening new pathways to treat diseases and monitor health, increasing aquaculture efficiency, and evolving new resources for industrial processes and materials (Querellou *et al*. 2010).

2.1.5 *Offshore energy:* While we are turning to greener options to meet our energy requirements, offshore wind energy is becoming more prevalent, particularly in Europe (Appiott *et al*. 2014). Other forms like wave, tidal, or thermal energy are progressing rapidly in Hawaii, with ocean thermal energy conversion and wave energy experimental programmes. These technologies are yet to be tried in coastal least developed countries (LDCs) and SIDS. Most coastal LDCs and SIDS currently rely on fuel imports to meet their energy demands, making them especially sensitive to global energy price fluctuations and disproportionately high transportation costs. Fuel imports accounted for 11.9% of GDP in SIDS in 2011, greater than healthcare spending.

Marine energy could be a source of clean, renewable energy for SIDS and coastal LDCs. SIDS have made slow progress toward renewable energy. Still, with the help of development partners, they have set ambitious goals to become less dependent on fossil fuels, with policies in place to promote the transition (Appiott *et al*. 2014).

2.1.6 *Deep-sea mining:* Mineral resources are found in the ocean basins and shallow continental edges, but deep basins are exploited for their potential economic benefit. Marine mining is not a brand-new business. From beaches and contiguous shallow waterways, mining of heavy minerals (gold, tin, titanium, zirconium, rare earths, and others), diamonds, and aggregates have been practised for much of the last century and even earlier (Baker *et al*. 2016). From water depths of around 150 to 250 m, gem-quality diamonds recovered from the seabed off the Atlantic coast of southern Africa constitute a multi-billion–dollar industry (Scott 2011).

Massive seafloor sulphides, polymetallic nodules, and cobalt-rich crusts have been the subject of interest for deep-sea mineral deposits (Beaudoin and Baker 2013a, b, c, d). The seafloor sulphide deposits contain high concentrations of copper, zinc, gold and silver; polymetallic nodules contain manganese, nickel, copper, molybdenum, and rare earth elements; and ferromanganese crusts have manganese, cobalt, nickel, rare earth elements, yttrium, molybdenum, tellurium, niobium, zirconium, and platinum (Baker *et al*. 2016). The Clarion–Clipperton zone holds more than 27 billion tons of manganese nodules, which have at least 7 billion tons of manganese, 290 million tons of copper, 340 million tons of nickel, and 58 million tons of cobalt as estimated by the International Seabed Authority (ISA) by using a 'biogeochemical model' (Scott 2011). However, both sulphide and nodule mining are not feasible due to technological and environmental hurdles.

Although not mining in common terms, the oil industry pioneered offshore exploration in the mid-twentieth century. This source currently accounts for roughly a third of global petroleum output, and it is growing as technology permits deeper installations (Scott 2011).

2.1.7 *Deep-sea fisheries:* In recent decades, deep-sea fisheries have become economically significant. Due to the over-exploitation of many shelf stocks, the quest for commercial fisheries went deeper offshore. Harvests of new target species increased by fishing in higher (200–700 m) and mid (700–1500 m) continental slope habitats (Watson and Morato 2013). For commercial fisheries, 'deep-sea' species often constitute species fished primarily deeper than 200–500 m (Clark 2001). However, as compared with shallow-shelf species, deep-sea fisheries species frequently include species with lower productivity (based on traits such as slower growth rates, higher longevity, and lower fecundity), as well as those that are often found on offshore topographic features like seamounts and ridges (Clark 2009). In 2012, 475,000 tons of deep-sea species were caught (FAO FishStat data). On a global scale, deep-sea fisheries are thus very small (representing 1% of marine fish catches) but constitute an essential component of the national catch in some areas (e.g., the Azores with 5000 tons of scabbardfish in 2012; New Zealand with 3200 tons of alfonsino, 6200 tons of orange roughy, 11,800 tons of oreos, and 128,000 tons of blue grenadier in 2012) (Clark *et al*. 2016).

2.1.8 *Shipping industry:* A significant form of transport for consumer goods, raw resources, and critical consumables worldwide is shipping. As a result, it is crucial to economic growth and employment both at sea and on land. In 2015, marine shipping contributed to more than 80% of all international goods commerce, which is much more significant for most developing countries. In terms of value, some analysts put marine seaborne trade at 55% of total international trade in 2013, while others put it at more than 70%. According to some predictions, international seaborne commerce volumes will likely double by 2030, while port volumes will quadruple by 2050 (International Transport Forum).

2.2 *Ecosystem services*

2.2.1 *Tourism:* Tourism is one of the world's major sectors, contributing trillions of dollars to the global economy and supporting the livelihoods of one out of every 10 people on the planet. By 2030, marine and coastal tourism will be the most valuable part of the ocean economy, accounting for 26% of ocean-based industries' overall value addition. Furthermore, the expansion of coastal ecotourism gives crucial livelihood options for many rural and low-resource communities. Diversification into tourism provides new avenues to complement primary incomes in seasonal sectors like fishing and farming. Fishers and farmers, for example, can opt to supplement their income rather than replace their primary source of revenue by developing new tourism services, activities, and attractions (Phelan *et al*. 2020).

2.2.2 *Oxygen source:* Plankton are not only an essential component of the marine food web but also have a considerable impact on climate and atmospheric composition, particularly the amount of oxygen in the atmosphere. Through the sea surface, oxygen enters the water and then into the air, adding to the overall oxygen budget in the atmosphere. The ocean phytoplankton is thought to produce around 70% of the oxygen in the atmosphere (Moss 2009). As a result, a decline in the rate of oxygen production by phytoplankton might have disastrous repercussions for life on earth, perhaps leading to the extinction of animal species, including humans (Sekerci and Petrovskii 2015).

2.2.3 *Carbon sequestration:* Oceans are considered the largest sinks of CO_2 from the atmosphere, with a size comparable to the terrestrial sinks. The mechanism of CO_2 sequestration helps in the even distribution of CO_2 through the ocean depths. Direct CO_2 injections into the deep ocean, comparable to geological sequestration, and ocean fertilization with iron to boost phytoplankton growth and photosynthetic rate are the two main proposed ways of ocean sequestration. The ambitious plan has many unknowns, but may help slow climate change. According to some models, putting CO_2 into the deep ocean will keep it isolated from the atmosphere for thousands of years, and it will only recycle back into the atmosphere after millennia. There are still doubts regarding the practicality of ocean sequestration, and there is lack of clarity regarding ocean biology and the chemical impacts that ocean sequestration may have on the environment (Hinge *et al*. 2020).

2.2.4 *Coccolithophores and cloud seeding:* Coccolithophores are widespread marine plankton components. They play a significant role in the oceanic carbon cycle through calcification and photosynthesis. Moreover, the marine food chain is founded by coccolithophores and other phytoplankton. The coccolithophores are preyed upon by zooplankton, and their cell contents are digested and assimilated; however, calcareous coccoliths are expelled and integrated into faecal pellets. Marine snow is formed as the coccoliths in these faecal pellets fall fast to the seafloor, loose coccoliths and coccospheres, and mix with other plankton debris (Honjo 1976). Thus, these two mechanisms considerably increase the sinking velocity of coccoliths and prevent them from dissolving in the water column. The sinking speed of faecal pellets is 150–570 m per day, and loose coccoliths less than 1 m per day. Therefore, coccoliths are quickly carried to the seafloor due to these two mechanisms and represent one of the chief components of marine sediments above the calcite compensation depth (CCD). Nevertheless, noteworthy dissolution and assemblage modification occur, as evidenced by only roughly 60 coccolithophore varieties known from the fossil record out of 280 identified from plankton (Hagino and Young 2015).

The common biogenic component added to the sulphur (S) flows from the hydrosphere to the atmosphere is the gas dimethyl sulphide (DMS) in marine waters. About 3 decades ago, the cloud seeding activity of DMS and its potential role in climate regulation were first postulated (Charlson *et al*. 1987). The enzymatic cleavage of dimethylsulfoniopropionate (DMSP) produces DMS, which is oxidized chiefly by the hydroxyl radical OH in the atmosphere (Marandino *et al*. 2013). Compared with other airborne particles originating from sea salts, dust, and anthropogenic pollutants, the relative relevance of atmospheric DMS oxidation products determines the significance of DMS-derived particles in impacting the earth's cloudiness and albedo (Quinn and Bates 2011). Phytoplankton bloom dynamics, notably speciation and development stages from start to senescence, are assumed to influence DMS distribution, first and foremost, through the varied production of DMSP by various phytoplankton members. DMSP is released into the aquatic environment primarily due to cell breakdown caused by ageing, grazing, or viral infection and, to a lesser extent, via active secretion by healthy algae (Lizotte *et al*. 2017).

2.2.5 *Warm glow services:* Warm glow services are one of the ecosystem services that include non-use values of the oceans. Non-use or passive-use values are those ecosystem services that exist even if they are not utilized. These consist of existence and bequest values, like cultural, heritage, spiritual benefits, and biodiversity studies, which refer to the public awareness of ecosystem services that will persist for future generations to enjoy (Mehvar *et al*. 2018).

3. Challenges

The blue economy faces challenges like HABs, invasive species, global warming, ocean acidification, marine pollution, and many more (figure 3), which are discussed below.

3.1 *Harmful algal blooms (HABs)*

There is plenty of evidence that the composition of coastal and offshore marine plankton and benthic ecosystems is already affected due to changes in the

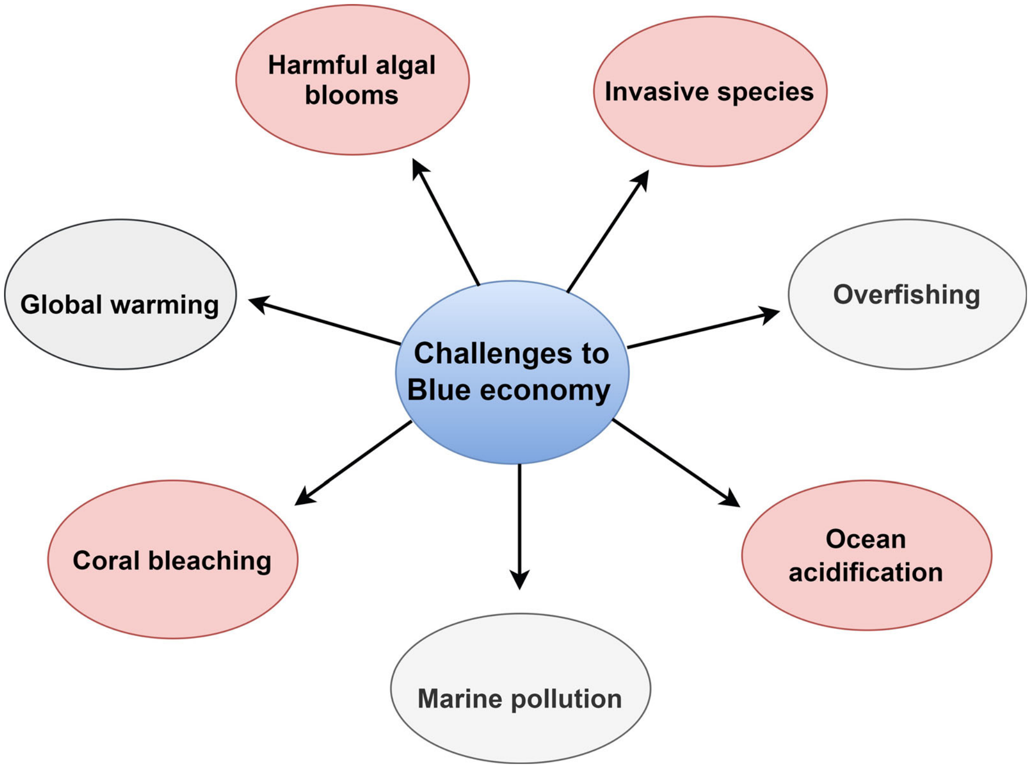

Figure 3. Challenges to the blue economy.

climate. Future climate changes will likely affect the geographical and temporal ranges of HAB species. These changes may increase the intensity and frequency of HABs, which are toxin-producing or high-'biomass' events (Wells and Karlson 2018).

3.2 *Invasive species*

Invasive species numbers and distributions are expanding in many parts of the world where biogeographic distinctions between regions are blurring. Invasive species costs in Europe are now estimated to be between €12.5 and €20 billion a year, and USD 120 billion in the US, although these figures are likely underestimated and will increase with time. Alien marine species can become invasive in marine ecosystems, displacing native species, causing the loss of native genotypes, altering habitats, changing community structure, affecting food-web properties and ecosystem processes, obstructing ecosystem services, affecting human health, and causing significant economic losses. In recent decades, rapid globalization and rising trade, travel, and transportation trends have intensified marine biological invasions by boosting the rate of new introductions via diverse paths like shipping, navigational canals, aquaculture, and aquarium trade (Gallardo *et al*. 2019).

3.3 *Global warming*

Since the industrial revolution, growing CO_2 concentrations, mainly from the combustion of fossil fuels, has increased global warming (IPCC 2013). From 1880 to 2012, the global mean surface temperature increased by 0.85°C, and it is anticipated to rise by 2.6–4.8°C according to the Representative Concentration Pathway (RCP) 8.5, the worst-case scenario in the IPCC report, which assumes emission rates at or below current levels of atmospheric CO_2 and emission acceleration. Temperatures higher by only 1–2°C above the normal summer maximum can cause mass coral bleaching and mortality (Berkelmans 2002).

3.4 *Ocean acidification*

Since the late 1950s, there has been considerable evidence that the ocean acts as a significant sink for anthropogenic CO_2, including direct reports of rising dissolved inorganic carbon (DIC) inventories (Gruber *et al*. 2019) which support the conclusion that the ocean absorbs roughly a third of total anthropogenic CO_2 emissions. However, the increased CO_2 in the sea causes a broad change in seawater acid–base chemistry, resulting in lower pH conditions and decreased saturation states for carbonate minerals in many marine organism shells and skeletons (Zeebe and Wolf-Gladrow 2001).

Moreover, the biomass of primary producers is increased by ocean acidification, but it reduces taxonomic diversity (Enochs *et al*. 2015). Functional consequences are anticipated to decline in taxonomic diversity, although the impacts on ecosystem function are still being investigated (Teixidó *et al*. 2018). Altered competitive interactions for food or space are attributed to community structure homogenization in space and time (Colossi Brustolin *et al*. 2019).

Harvests of some bivalve shellfish species will almost certainly reduce due to ocean acidification, resulting in cultural disturbance and revenue loss (Doney *et al*. 2020). During the mid-2000s, the Pacific oyster aquaculture business in the Pacific Northwest sustained over 3000 jobs and USD 270 million in annual economic activity, despite being increasingly threatened by acute ocean acidification exacerbated by increased coastal upwelling (Barton *et al*. 2015). Of the total world fishing production, marine molluscs account for 9% (Narita *et al*. 2012); therefore, the possible impact of ocean acidification on shellfish harvests and ecosystem services became a research subject (Cooley and Doney 2009). Bivalve reproduction, juvenile bivalve survival, and adult maturation are all affected by ocean acidification, which can affect recruitment, harvestable biomass, economic value, and maximum sustainable yield of shellfish fisheries (Cooley *et al*. 2015).

3.5 *Overfishing*

A significant amount of food is obtained from marine fisheries, and it is a source of income for people worldwide. Yet, there are fears that current fishing practices threaten the extinction of several marine species. Many common commercial fishing techniques, such as trawling, long lining, and seining, catch many species simultaneously. Multispecies fisheries are particularly vulnerable to extinction or severe depletion because fishing can be profitable as long as certain desirable species are numerous, even if others are declining. In a single-species fishery, on the other hand, revenues tend to diminish as the target population shrinks, removing the incentive to fish before extinction (Burgess *et al*. 2013).

3.6 *Coral bleaching*

One of the highly diversified marine ecosystems on the planet is coral reefs. They generate billions of dollars in economic value through coastal preservation, tourism, food, and pharmaceuticals (Costanza *et al*. 2014). Coral bleaching events, in which corals lose their endosymbiotic algae, the primary energy source for most reef corals, are becoming more common and intense as sea surface temperatures rise (Pandolfi *et al*. 2011). Coral bleaching can cause coral morbidity and death, resulting in drastic changes in coral community composition, loss of coral cover, and rapid rearrangement of coral reef fish populations (Stuart-Smith *et al*. 2018).

3.7 *Marine pollution*

Marine pollution is a global issue that affects the health of the oceans worldwide, including both developed and developing nations, and all countries contribute to this problem. More than 80% of marine pollution is due to land-based sources. Marine pollution is a composite of plastic waste, toxic metals, oil spills, industrial effluents, sewage, fertilizers, pesticides, and agricultural runoff. Among them, pollution due to plastic debris is a major threat to marine life. The annual entrance of plastic into seawater is more than 10 million tons (Jambeck *et al*. 2015), and more than 80% of marine litter is plastics, according to the European Parliament (2019). Single-use plastic items contribute to 50% of the plastics that enter the marine environment, as reported based on river, beach, and ocean survey studies (Jambeck *et al*. 2015).

As plastics are long-standing and have limited degradation, secondary breakdown (weathering and fragmentation) results in the formation of microplastics, which can cause more adverse effects on the health of marine organisms (including inflammation, blockage of intestinal tracts, oxidative stress, reproductive impact, and hormone disruption) (Almroth and Eggert 2020). Microplastics also affect the health of humans as they are increasingly found in seafood and water resources.

Ocean pollution with oil is often associated with oil spills, runoffs, routine shipping, and dumping. Polycyclic aromatic hydrocarbons (PAHs), toxic metals, heavy and light hydrocarbons, and other chemicals are petroleum products and crude oil components. They may be released into the marine environment due to oil spills or leaks in tanks, and then they cause massive damage to marine life. They bio-accumulate in the food web, destroy commercial fisheries' shellfish beds, kill marine mammals and birds, foul shorelines, and release volatile chemicals into the atmosphere. In recent years, the frequency of spills has increased due to the rise in global demand for petroleum. The Deep Water Horizon oil spill in the Gulf of Mexico and the Fukushima nuclear power plant accident in Japan are well-known events in recent times (Landrigan *et al*. 2020). Table 1 summarizes some of the major oil spills of history year-wise.

4. Sustainability in the blue economy

Ocean health determines economic development and human well-being. Since the 1992 Earth Summit, there has been a steady increase in attention to ocean sustainability, which has increased with the adoption of the Sustainable Development Goal (SDG) 14: Life Below Water in 2015. However, ocean-based enterprises and human activities have a considerable negative impact on marine systems. More exploitation and new industries will add to the already stressed state of marine habitats. Seabed mining, for example, is a new form of development with unknown risks. Furthermore, the cumulative effects of existing and emerging ocean activities and climate change-related stresses are little known. Policy frameworks and environmental assessment systems for understanding and managing environmental risks of maritime development are either in the early stages or do not exist at all (Bennett *et al*. 2019).

Table 1. Major oil spills of history

	Spill and location	Year	Spill size (tons)
1	Ecofisk, Norway	1977	27,000
2	Ixtoc I, Mexico	1979	4,75,000
3	Funiwa 5, Nigeria	1980	26,000
4	Nowruz, Iran	1983	40,000
5	Exxon Valdez, Alaska, USA	1989	40,000
6	Montara, Australia	2009	20,000
7	Deepwater Horizon Oil Spill, Texas, USA	2010	5,100,000
8	Guarello Island, Patagonia, Chile	2019	40

Coastal economies could be revitalized, new livelihoods might be provided, and food security and well-being could be enhanced. SIDS and coastal governments may be able to reclaim sovereignty and access to marine resources due to new economic prospects. The idea of a 'trickle-down' blue economy, on the other hand, is problematic. Unregulated economic growth can result in economic inequity, adverse social and cultural consequences, displacement of local inhabitants, and exposure of marginalized groups to pollutants. As evidenced by the global fishing industry, unchecked growth can lead to human rights violations such as enslavement and destruction of local access to fisheries and food security. According to international social groups, 'ocean grabbing' occurs as ocean resources and spaces are privatized for growth. Similar difficulties have been noticed in other maritime industries (such as oil and aquaculture), with global summits discussing the need for social equality and 'blue justice'. At the 2018 Sustainable Blue Economy Conference in Kenya, specific concerns about the indigenous people, small-scale fisheries (SSFs), women, and youth were prominently discussed. The rhetoric of equity, benefit-sharing, and inclusion, on the other hand, appears to be outperforming policy-making and best-practice implementation (Bennett *et al*. 2019).

5. Way forward

5.1 *Effective policies and sustainability*

The Indian Ocean is the world's third largest maritime division, comprising more than 70 million square kilometres and including significant exclusive economic zones (EEZs) of several countries and noteworthy 'high seas'. The economic and sustainable development on the Indian Ocean rim is challenging as the bulk of the littorals are in developing countries. One-third of the world's population, which rely heavily on marine resources for their food and livelihood, lives in these countries. Pollution, habitat deterioration, and over-exploitation are all stresses on the Indian Ocean's resources due to the sheer size of this ecosystem. As the region's population is estimated to grow dramatically in the future decades, the impact of marine resources on food security and the economy will become more significant.

Furthermore, climate change impacts such as sea-level rise, ocean acidification, and extreme weather events pose multi-dimensional challenges in this region, including changes in community structures due to migration, aquatic species distribution alterations, and decreased economic productivity. Serious efforts are required to assure global food security, alleviate the mounting constraints on ocean resources, and secure the livelihood of future generations. Thus, Goal 14 of the Sustainable Development Goals says that increasing collaboration in conserving and sustainable use of seas, oceans, and marine resources is critical. The Indian Ocean Rim Association (IORA) emphasized in their September 2015 Mauritius Declaration on Blue Economy (Roy 2019) the need for immediate action towards improving governance frameworks to conserve the ocean's resources for future generations.

Gunter Pauli (2010) coined the term 'blue economy' in 2010, and it was later debated at the United Nations Conference on Sustainable Development, Rio, in 2012. The blue economy has now become a powerful and contentious notion in the Indian Ocean region, with member states of the primary regional governance organization, IORA, debating it (Premarathna 2021). Several IORA states have been strongly lobbying for stronger collaboration and improved blue economy governance from its conception. Bangladesh, for example, has been at the forefront of regional efforts to promote the blue economy, hosting the first major conference in 2014 focussed on creating the Bay of Bengal collaboration for the blue economy (Premarathna 2021). This was followed by an IORA-organized conference in 2015, called 'enhancing blue economy for sustainable development'. As a result of these initiatives, the Indian Ocean region's focus on sustainable development has shifted, and the IORA Declaration on Enhancing Blue Economy Cooperation for Sustainability has emerged (Roy 2019).

The right to approach natural resources and an environment conducive to human health that talks about sustainable development and ecological integrity are clearly provided in South Africa's Constitution; environmental conservation has a primary priority. Many policies and laws have been enacted in the country, including the National Environmental Act of 1998, the Integrated Coastal Management Act of 2008, the Disaster Management Act, the Biodiversity Act of 2004, and the Environment Conservation Act of 1989, all of which are aimed at addressing sustainable development challenges, intergenerational equity, and the right to a favourable environment. Furthermore, the Marine Living Resources Act 1998, which covers spatial planning, commercial fishing licence permits, and sustainable use of marine resources, has a distinct specialized regulation for fisheries. Despite this, there is still a scarcity of coordinated initiatives directly targeting issues, such as food security and climate change.

In the meantime, Mozambique has passed legislation such as the Forestry and Wildlife Law, the Fisheries Law and Local Organs of State Law, the Environment Law of 1997, and the National Adaption Programme of Action of 2007, all of which focus on integrated and sustainable marine environmental management and climate change mitigation. Various international treaties provide a shared framework for developing law and policy in the Indian Ocean region. The majority of Indian Ocean countries have ratified significant international environmental accords and ocean governance frameworks that establish commitments to protect and conserve the ocean environment: The United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Biological Diversity (CBD), the Convention on Migratory Species (CMS), the Convention on International Trade in Endangered Species (CITES), the United Nations Convention on the Law of the Sea (UNCLOS), and the Agreement on the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks are among them. However, there is lack of precision in achieving the objectives put forth in most of these agreements. The United Nations Environment Programme (UNEP) Regional Seas Program, which spans 18 regions worldwide and includes India, Bangladesh, Sri Lanka, Pakistan, and the Maldives, focusses on Integrated Coastal Zone Management, environmental consequences, and climate change challenges (Roy 2019).

5.2 *Lowering carbon footprint*

The phrase 'carbon footprint' has become frequently used in public debates on steps that must be taken to mitigate the threat of global climate change. In general, a carbon footprint refers to a specific amount of gaseous emissions linked to climate change produced or consumed by humans. Bio-based plastics emit fewer greenhouse gases during their life cycle than fossil fuel-based equivalents (Chen and Patel 2012). It is anticipated that replacing 65.8% of the world's conventional plastics with bio-based polymers will reduce 241–316 million tons of CO_2 equivalents (CO_2e) per year (Spierling *et al.* 2018).

Another method for lowering life-cycle greenhouse gases (GHG) emissions of plastics is to use low-carbon energy. GHG emissions from US plastics manufacturing might be decreased by 50–75% under a 100% renewable-energy scenario (Posen *et al.* 2017).

Recycling is another option for reducing GHG emissions from plastics, as it decreases carbon-intensive virgin polymer production (Hopewell *et al*. 2009) and also prevents GHG emissions from some end-of-life (EoL) processes like burning (Lazarevic *et al*. 2010). A scenario for energy decarbonization shows a significant reduction in GHG emissions. GHG emissions from plastics would lower by 62% in 2050 by switching to a 100% renewable energy life-cycle, assuming a 4% per-year demand growth. Even if fossil fuels (natural gas, petroleum, and coal) constitute the sole source of energy for future plastics manufacturing, employing 100% renewable energy can reduce emissions by 51% (projected EoL mix) compared with the baseline; however, absolute total emissions would double the 2015 level by 2050 (Zheng and Suh 2019).

5.3 *Reducing plastic pollution*

Plastic accounts for about 10% of total solid garbage and for up to 80% of waste on land, shorelines, ocean surface, and seabed. The main issue with plastic is that a large amount of it is utilized to construct disposable packaging goods or other short-lived items that are discarded forever within a year of manufacture (Hopewell *et al*. 2009). Every day, approximately a billion single-use plastic bags are distributed free. About 0.2 to 0.3% of all plastics produced ends up in the ocean (Andrady and Neal 2009).

Plastics rarely biodegrade, but they fragment into microplastics and nanoplastics through various mechanisms, and these have been identified as pervasive pollutants in all marine ecosystems worldwide. Microplastics are separated into two categories based on their origin/source in aquatic environments: primary and secondary microplastics. Both primary and secondary microplastics are found in various amounts in all marine environments, and approximately 245 million tons are discharged into the ocean each year. From the Arctic to the Antarctic, microplastics have overwhelmed many aspects of oceans and seas, including shorelines, beaches, seabed sediments, and surface waters (Kukulka *et al*. 2012). Their small densities (in comparison with water), sources of production and discharge into the environment, mechanisms of dispersion (via ocean currents and or wave directions), and hydrodynamic processes of the water body all contribute to the global distribution of these particles across the globe (Alimba and Faggio 2019).

Almost all marine species, from plankton to marine mammals, and including some of the world's wildest and most vulnerable species—creatures that spend nearly their entire lives away from humans—now have plastic in their bodies. From 1986 to 2008, 60% of 6,136 surface plankton net tows done in the western North Atlantic Ocean and the Caribbean Sea contained buoyant plastic fragments ranging in size from millimetres to centimetres (Law *et al*. 2010). Plastics have been found in bird nests, hermit crabs' shells, and the stomachs of sea turtles, whales, and albatrosses (Mrosovsky *et al*. 2009). Over 260 species have been recorded to consume or become entangled in plastic trash, including invertebrates, turtles, fish, seabirds, and mammals, resulting in restricted locomotion and feeding, reduced reproductive output, and increased lacerations, ulcers, and death. One of the most noticeable effects of plastic pollution is entanglement of marine creatures in abandoned or lost plastic netting, rope, and monofilament lines from commercial fishing. Pods of endangered humpback whales have been spotted travelling north with a pile of tangled rope in tow (e.g., crayfish pots and buoys with marker pole and flag). Fishing gear that are lost, discarded, or derelict can continue to trap fish and other species for an extended period of time (Wabnitz and Nichols 2010).

6. Conclusions

The oceans cover 72% of the earth, but still, there is little knowledge about oceans, especially the deep ocean. A new term, blue economy, was coined by Gunter Pauli in 2010, later accepted by the United Nations (UN) and now become part of sustainable development for most nations. It is estimated that around 3.1 billion people rely on oceans for 20% of their animal protein intake. Oceans provide food in the form of fisheries, aquaculture, and seaweed farming. Over the last 50 years, the global macroalgae sector has grown exponentially. It rose at an average yearly rate of 8.13% in quantity and 6.84% in monetary value between 2003 and 2012. Aquaculture produced about 23 million tons of macroalgae (dry weight) in 2012, worth over 6 billion USD. The ocean provides various value-added products like agar, alginate, carrageenan, ecteinascidin, salinosporamide A, antifouling agents, development luminase, ambergris, feed and fertilizer, and carotenoids. The oceans also provide offshore energy, support the tourism and shipping industry, and help in cloud seeding. Ocean health is connected to economic and human well-being. Since the 1992 Earth Summit, attention to ocean sustainability has increased with the adoption of SDG 14: Life Below Water in 2015. However, human activities and ocean-based enterprises negatively impact marine systems. Blue economy helps in achieving economic growth, provide livelihoods, and, most importantly, prevents ocean health from depleting. However, the blue economy faces various challenges that hinder its sustainability. Some of the challenges faced by the oceans are the HABs, invasive species, global warming, ocean acidification, coral bleaching, and thermohaline circulation, which negatively affect the blue economy. Henceforth it becomes more and more vital to make the blue economy sustainable so that future generations could be benefited from it, and this sustainability can be achieved by reducing our carbon footprint, by reducing the use of plastics which degrade into microplastics and harm the organisms living in the oceans.

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Author contributions

SN and FB conceptualized the study, and SN, MK, and DSY contributed to data acquisition, writing, reviewing, and editing of the manuscript. FB secured the funding for the study from DST-SERB, GOI. The final manuscript was read and approved by all authors.

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