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Vazhiyil VenugopalView Article Online
DOI: 10.1039/D5FB00682A**Final Manuscript (Ms. No. FB-REV-10-2025-000682R4)****Sustainability spotlight of the article**

Sustainable fisheries are interlinked with resource conservation, environmental protection and economically as well as socially sound production strategies. The proportion of fishery resources available within biologically sustainable levels, however, has been declining in recent decades due to environmental and other challenges, adversely affecting food security of the rising global population. There is an urgent need to address these challenges for sustainable seafood production. Modern strategies for sustainable production rely on science-based blue transformation protocols related to fishing operations, aquaculture as well as transformation of voluminous fishery discards generated along the supply chain into ingredients as well as bioenergy useful in diverse industries. The article highlights science-based transformation of fisheries can meet sustainable development goals of the United Nations 2030 Agenda.



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CHECKED MANUSCRIPT***4 May, 2026**View Article Online
DOI: 10.1039/D5FB00682A**Ms. No. FB-REV-10-2025-000682R4****BLUE TRANSFORMATION PROTOCOLS FOR RESILIENT AND SUSTAINABLE
SEAFOOD: AN OVERVIEW****VAZHIYIL VENUGOPAL**
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ABSTRACTView Article Online
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Availability of fish and shellfish is stretching beyond sustainable limits due to environmental and other challenges. These include global warming, habitat destruction, ocean acidification, biodiversity loss, pollution, destruction of corals and mangroves. Furthermore, over-fishing, voluminous by-catch as well as process discards along the supply chains adversely affect seafood security and bioeconomy. A cohesive and transformative approach is urgently required to address the challenges for resilient and sustainable fishery production. The Food and Agriculture Organization (FAO) of the United Nations suggested blue transformation to build sustainable, resilient and inclusive fisheries and aquaculture. The three-point action plan to transform aquatic food systems by 2030 and beyond calls for: (i) effective management of fishery stocks through control of overfishing, bycatch landing, and climate actions to minimize global warming, (ii) sustainable aquaculture, and, (iii) upgradation of aquatic value chain for social, economic and environmental sustainability. This article, at the onset, briefly discusses challenges facing sustainable seafood production followed by conventional practices to address these challenges. It then discusses science-based blue transformation protocols that are able to remove weaknesses and encourage resilience of fishery production. Environmentally-friendly green technologies are able to decarbonize fishery production systems and transform fishery discards into diverse nutraceuticals, industrially important ingredients and also biofuel. Nature-positive aquaculture operations can enhance resources under environmentally friendly conditions. The blue transformation protocols, integrated with zero-waste, circularity and digitalization strategies, can minimize environmental hazards, encourage resilience and steer sustainable seafood production that can also meet the Sustainable Development Goals of the United Nations 2030 Agenda.



Key words: Sustainability challenges, habitat conservation, global warming, innovative aquaculture, waste valorization, seafood sustainability.

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Sustainable fisheries are interlinked with resource conservation, environmental protection and economically as well as socially sound production strategies. The proportion of fishery resources available within biologically sustainable levels, however, has been declining in recent decades due to environmental and other challenges, adversely affecting food security of the rising global population. There is an urgent need to address these challenges for sustainable seafood production. Modern strategies for sustainable production rely on science-based blue transformation protocols related to fishing operations, aquaculture as well as transformation of voluminous fishery discards generated along the supply chain into ingredients as well as bioenergy useful in diverse industries. The article highlights science-based transformation of fisheries can meet sustainable development goals of the United Nations 2030 Agenda.



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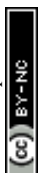
1.0 Introduction

The aquatic foods, fish, shellfish and seaweeds, are also called, 'blue foods'. Blue foods have crucial roles in meeting food security. Both the wild caught and farmed fish as well as shellfish are essential components of global food security, providing consumers nutrition, health, and living. The wild catch includes finfish, crustaceans and molluscs from the ocean, rivers, ponds, lakes, estuarine, and other water bodies. The popular finfish items include anchoveta, herring, tuna, mackerel, pollock, whiting, and others, while major shellfish species encompass shrimp, lobster, oyster, mussel scallop, clam, crab, krill, crayfish, squid, cuttlefish, snail, and abalone. Preferred shellfish and finfish species are also raised by farming operations undertaken in fresh (aquaculture) and marine (mariculture) waters. In this article, the term seafood is used as a general term for fishery products, irrespective of their habitat origin. According to the Food and Agriculture Organization (FAO) of the United Nations, in the year 2022, the total fish and shellfish raised were 223.2 million metric tonnes (Mt), of which 89 percent was used for human consumption. Sixty-two percent of the aquatic animals were harvested from marine waters (69 percent from wild capture and 31 percent from aquaculture), and 38 percent from inland waters (84 percent from aquaculture and 16 percent from capture). Worldwide about 730 fishery items are raised by aquaculture, of which 17 staple species constituted about 60 percent of worldwide aquaculture production of 130.9 Mt. Decapod crustaceans - shrimp, lobsters, crayfish, and crabs - are among the most economically significant farmed species due to their high consumer value. Pacific white-leg shrimp (*Penaeus vannamei*) contributed 53 percent of the world's shrimp production, at a market value of around US\$ 36.5 billion during 2022. During this period, over 230 countries traded aquatic foods worth US \$ 195 billion. The global average per capita fish consumption rose from 15.6 to 20.4 kg per year, on a live-weight basis between 1998 and 2018. With a



current per capita consumption of 20.7 kg, consumer demand for aquatic foods is projected to touch 232 Mt by 2030 (1). Fish consumption is expected to rise further when the world population is likely to cross about 9.8 billion in 2050. Total consumption of fish and also agricultural commodities is projected to grow by 13% from current levels by 2034 to reach a per capita consumption of 21.8 kg by 2034 (2). Fishery items are generally rich in various nutrients including proteins, peptides and essential amino acids, long-chain omega-3 polyunsaturated fatty acids (PUFA), particularly eicosa-pentaenoic acid (EPA) and docosa-hexaenoic acid (DHA), carotenoids such as astaxanthin and β -carotene, various vitamins and minerals, making them crucial for global nutritional security (3). Rising awareness of nutritional value of fishery products encourages increase in consumption. Aquatic foods can have significant role in fighting hidden hunger, a problem of micronutrient deficiency, when individuals lack essential minerals (iron, calcium, zinc, iodine, and selenium), and vitamins A and D (4).

Fisheries and aquaculture, however, face rising uncertainties due to changes in environmental conditions, trade tensions and evolving sustainability priorities. Sustainable aquaculture faces challenges, such as environmental, climate, and resource factors, demanding significant efforts to keep fisheries production sustainable (2). Most of the current efforts in this regard have been traditional in nature such as restricting fishing quota, maintaining protected fishing areas, etc., which have limitations in sustainable production. In view of worsening geo-political and environmental problems as well as rising consumer demand, a need has been felt for effective, eco-friendly and science-based practices for sustainable seafood production. Recently, the FAO called for a '*Blue Transformation Action Plan*' based on three approaches, namely, *conservation*, *innovative aquaculture* and *supply chain transformation*, to integrate aquatic foods into global food security and sustainability. The Action Plan aims to sustainably enhance aquatic food systems to improve food security,



nutrition and livelihood (1). This article, essentially relying on recent literature, attempts to discuss the role of multi-disciplinary transformative and collaborative efforts, innovative aquaculture and value chains upgradation including valorization of fishery discards for sustainable fisheries production. Importance of these measures in realizing sustainable development goals of the United Nations 2030 Agenda has also been pointed out. At the onset, the article, briefly discusses various challenges facing sustainable fisheries, which include illegal and overfishing, landing of voluminous quantities of bycatch, global warming and associated hazards, pollution, and others.

2.0 Challenges facing resilient and sustainable fisheries

Fisheries are crucial to food security and nutrition and global economy. Maintaining sustainable fisheries has ecological, environmental, social and economic importance. This requires the fisheries production systems should be resilient. Resilience is defined as the capacity of a system, or interconnected systems, to absorb disturbance and reorganize while undergoing changes so as to still retain essential function, structure, identity and feedbacks. Improved management and adaptation planning can improve fisheries resilience and mitigate impacts of environmental changes (2). Resilience contributes to sustainable development, described as a balancing act where shortfalls in providing a minimum social foundation for all are avoided, while making sure not to overshoot the ecological ceiling (5). A sustainable food system guarantees food and nutrition security, mitigate climate change, create sustainable economic growth and jobs while operating within the planetary boundaries to protect the ecosystems. A sustainable aquatic food system maintains healthy fish or shellfish populations, protecting the habitats, ensuring their availability for future generations, while supporting the livelihood of fishing communities. The term, 'Maximally sustainably fish' refers to stocks that are, on average, maintain 40 to 60 percent of their unfished biomass level. Stocks above 60 percent of the unfished biomass are considered underfished, and those



under 40 percent, overfished (6). Sustainable fisheries are capable to achieve goals related to (i) environment (minimising impacts on pollution, biodiversity, land and water use), (ii) ecology (maintaining the target species at or above the levels necessary to ensure their continued productivity), (iii) social (affecting people, particularly for those dependent on the fishery for their livelihoods), and, (iv) blue economy (supply of sufficient quantities of biomass feedstocks at reasonable prices). In order to achieve these objectives, fisheries production should operate on principles that minimise negative impacts on marine life, adapt to climate change and protect biodiversity, while supporting supply chain resilience and enhancing the health, wellbeing of communities (7). Figure 1 shows the four pillars for sustainable fishery management.

The major challenges of sustainable production with respect to capture fisheries are overfishing, destructive fishing, illegal, unreported and unregulated (IUU) fishing, habitat destruction, water pollution, and global warming related hazards such as ocean acidification, depletion of oxygen, loss of biodiversity, erosion of coastal ecosystems, migration of species, introduction of invasive species, and others. As a result of these problems over the past 30 years, landing of global capture fisheries have more or less plateaued around 100 Mt. The +12 percent increase in global capture fish production of the current decade is substantially lower than the 24 percent (37 Mt) increase achieved over the previous decade (2). The Marine Conservation Society (MCS) has downgraded sustainability status of cod, langoustine, and mackerel in the United Kingdom due to environmental concerns. The rating comes after the International Council for the Exploration of the Seas (ICES) recommended stoppage of commercial cod catch in 2026 for fisheries in the Northern Shelf, which includes U.K. fisheries (St. Onge, A., Seafood Source News, Global Spotlight, April 17, 2026, astonge@divcom.com, accessed, 2 April 2026). Challenges with respect to aquaculture relate to water quality, habitat disturbance, nutrient pollution as well as disturbances due to global



warming (8). The major challenges facing sustainable seafood production are briefly discussed:

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2.1. Overfishing, illegal fishing and by-catch

It has been estimated that some 4.9 million fishing vessels of all sizes ply the oceans, many with increasing capacities and efficiencies, annually capturing fish and shellfish between 86 and 94 Mt (9). As a result of intense fishing activities and also other problems, resource depletion is a major challenge facing global capture fisheries. Marine fishery stocks within biologically sustainable levels decreased to 62.3 percent in 2021, 2.3 percent lower than in 2019 (6) (1). Overfishing is a major concern, which affects stocks, undermining the resilience and biodiversity profile of the eco-systems, damaging resource potentials, and ocean economy. Globally about 37.7 percent of marine fish stocks are considered overfished, while a further 61 percent fully exploited and 29 percent of fishing grounds remaining overfished. Destructive fishing gears, pelagic trawls, shrimp trawls, purse seines, high sea driftnets, etc. not only endanger target species but also disrupt fish eggs, fry and juveniles, as well as non-target species. Some of the overexploited species include South American pilchard, Southern hake, tuna, jumbo flying squid, and others (1). Illegal, unreported and unregulated (IUU) fishing often targets high-value demersal species such as cod, salmon, trout, lobster and shellfish, particularly, shrimp causing harm to habitats and to sustainable ocean economy (10). It has been reported that over 90 endangered fish and invertebrates are caught in industrial fisheries (11) (12). Destructive fishing in Bangladesh resulted in catch of a total of 60 fish species including 6 crustacean species. Of these, 26 percent were classified as threatened, vulnerable, endangered, or critically endangered (13). Analysis of standardized catch per unit effort (CPUE) and spawning potential ratio (SPR) in Indonesia showed that most fishing practices were overexploited and unsustainable (14). Understanding tipping point dynamics is of crucial importance for sustainable resource



management. Western Baltic cod is beyond such a tipping point caused by unsustainable exploitation levels that failed to account for changing environmental conditions (15).

Hydraulic dredging, perhaps the most damaging method of trawling, digs deep into the sediment destroying as much as 41% of organisms. It requires several years to recover from the damage (16).

Landing of considerable amounts of low value fish, which are accidentally caught as bycatch while targeting popular items, is another major concern with respect to conservation and resource management. According to the World Wildlife Foundation (WWF), bycatch makes up 40 percent of fish catch worldwide, about 38 Mt including 300,000 small whales and dolphins, 250,000 endangered turtles and 300,000 seabirds (<https://www.worldwildlife.org/>, accessed 26 February, 2026) Bottom trawling for shrimp is responsible for high amounts of bycatch. A study of Northern Peru shrimp trawlers operating between April 2019 and March 2020 showed that bycatch constituted as high as 82 percent of total landing (17). Assessment of bycatch and discards in marine capture fisheries from Navi Mumbai, India, showed presence of a total of 101 species which included juveniles and subadults of commercially valuable organisms. The landing consisted of 29 species of fin fishes, 22 species of crustaceans, 31 species of gastropods, 11 species of bivalves, 3 species of cephalopods, 4 species of polychaetes and 1 species of sponges (18). Extremely rare pelagic “telescope” octopus was caught in the Indian Exclusive Economic Zone as bycatch during near-bottom trawling for deep-sea shrimp (19).

Small scale fisheries (SSF), also referred as artisanal fisheries, play an essential role in ensuring global food security, providing at least 40 percentage (about 37 Mt) of global fisheries catches (20). The fisheries are typically labour-intensive, relying on low-impact gear, and supplying local and regional markets with nutrient-rich proteins. SSFs are under increasing pressure from a complex web of socioeconomic and ecological challenges



including overfishing, habitat degradation, climate change, pollution, and postharvest losses leading to serious environmental and sustainability strains (21). Catches of most small pelagic species have declined after the 1980s. A sizeable amount of SSF goes for feed production for the aquaculture industry (12).

2.2. Global warming

Global warming is the most severe environmental threat of modern times, causing substantial economic and social damage. Warming, is primarily due to anthropogenic activities, responsible for rise in the levels of greenhouse gases (GHG) in the atmosphere, which act as heat-trapping agents, causing rise in average global temperature. The GHGs include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and fluorinated gases such as hydrofluorocarbons. The global net GHG emissions were 59 ± 6.6 GtCO₂-eq in 2019, about 10 percent higher than in 2010 and 54 percent higher than in 1990 (26). Recent increases in global surface temperatures have been tightly coupled with increases in CO₂. According to the Global Atmosphere Watch (GAW) Report of the World Meteorological Organization (WMO), the year 2024 was the hottest in the 175-year observational period. During the year, global surface temperature increased 1.55 °C above pre-industrial levels, when the globally averaged surface concentrations for CO₂, CH₄ and N₂O reached unprecedented high levels at 424 ppm, 1942 ppb and 338 ppb, respectively. As a consequence, most rivers, reservoirs, lakes, groundwater, and glaciers showed significant departures from normal temperature conditions, with only one third of river basins maintaining normal conditions in 2024 (22). The Emissions Gap Report-2025 of the United Nations Environment Programme (UNEP) observes that nations remain far from meeting the 2015 Paris Agreement goal to limit warming to well-below 2°C, while pursuing efforts to stay below 1.5°C. There is a need to reduce 55 percentage of annual emissions, compared with 2019 levels, to reduce average temperature 1.5°C by the year 2035 (23).



The ocean serves as a primary heat reservoir, absorbing about 90 percent of the heat added by climate change. Global warming related events cause rise in sea levels, increased shifts in ocean circulation, accelerated ice sheet loss, ocean currents, heat waves, melting of glaciers, floods, ocean acidification, diminished oxygen availability, collapse of coral reef ecosystems, and others. The effects of climate change on the Arctic are intensifying rapidly, with temperature rising three times the global average, resulting in accelerated melting of ice, causing rising sea level and extreme weather events (Pillai, A. K. B., <https://www.academia.edu/s/41b8df7d02#>, accessed January 23, 2026). Warming and loss of sea ice exacerbated collapse of eastern Bering Sea snow crab (24). The photic zone of the ocean, about 200 m deep on an average is habitat of fishery stocks, where sufficient light penetrates to stimulate photobiological processes. Rising temperature causes changes in the optical properties of the photic zone associated with darkening of the zone. The darkening causes a reduction in the depth to which photobiology can function resulting in habitat loss to fisheries. The last two decades have witnessed about 10 percent reduction in the depth of fishery biomass-rich photic zone (25).

Food systems including fisheries contribute 23 to 42 percentage of global GHG emissions. Absolute GHG emissions from food systems increased from 14 to 17 Gt CO₂-eq per year in the period 1990 to 2018 (26). Cradle-to-grave emissions from food loss and waste represent half of total GHG emissions from food systems (27). Global fishing activities are estimated to emit about 180 Mt CO₂e annually, approximately 4 percent of total GHG emitted by global food systems (9) Shifting diets towards fish products is capable to reduce emissions by up to 125 MtCO₂e per year compared to baseline scenarios (27). GHG emissions with respect to fish and shellfish, however, differ on capture or cultivation conditions. Life-cycle analysis data from wild-caught and farmed seafood products, covering



over 1690 fish farms and 1000 records were compared. Capture fisheries predominantly generate GHG, with small pelagic fishes generating lower emissions than all fed aquaculture, but flatfish and crustaceans generating the highest. Farmed silver and bighead carps have the lowest GHG, nitrogen and phosphorus emissions, but highest water use. Across all blue foods, farmed bivalves and seaweeds generate the lowest stressors. The data allow to identify high-performing blue foods, highlighting opportunities to improve environmental performance and develop sustainable diets (28). Table 1 gives values of GHG emissions by some wild and farmed seafood items.

2.2.1. Influences on fisheries. Climate change affects primary fishery production in the marine ecosystems, species and stock distributions. Climate change is shifting species with warm-water species moving into temperate zones, altering the eco-systems (29). The temperature rise affects physiological functions, biomass, nutrient composition, oxygen consumption, food intake, moulting, life cycle, immune response, behavioural changes, feeding, reproduction and others. Extreme events have resulted in substantial declines in populations and fish biomass. Long-term ocean warming and marine heatwaves pose serious threats eventually leading to fisheries collapse impacting food security and economies, particularly in tropical regions (30). Climate-induced declines in ocean health can cost the global economy \$428 billion per year by 2050 (26). A recent exhaustive study analysed changes in biomass of 33,990 fish populations (1,566 species) covering major Northern Hemisphere basins during the period 1993 to 2021. Long-term warming was associated with a decline of fish biomass up to 19.8 percent per year. On shorter timescales, warmer years and marine heatwaves caused sharp biomass losses of up to 43.4 percent. These changes underscore the critical role of climate change in adversely impacting food production, calling for integrated land-sea management approaches in ensuring global food security (31,32). El



Niño events have affected marine fisheries in 11 of the 19 major fishing areas causing declines in fish catch in the East and North Pacific and the East China Sea (1). Climate events intensify landing of bycatch, stranded and invasive marine species. Changing ocean conditions, driven by temperature increases, have led to shifts in abundance of lobster, its distribution, larval settlement, disease prevalence, and ultimately changes in its landing pattern. The behavioural changes were due to temperature effects on spawning, larval development, mating behaviour and related reasons (33). Rising ocean temperature can adversely affect absorption of minerals by shellfish such as oysters, clams, lobsters and shrimp leading to poor shell formation, changes in species-specific thermal tolerance, seasonal dynamics, reproductive cycles and life stages, affecting seafood sustainability. Using an integrated climate-biodiversity-fisheries-economic impact model, it has been forecast that on average, when an annual high temperature extreme occurs in an exclusive economic zone, 77 percent of exploited fishes and invertebrates are likely to decrease (34). *Vibrio* spp. including *V. parahaemolyticus* and *V. vulnificus* are major foodborne pathogens found in marine environments. Fishery items are susceptible to contamination by these pathogenic organisms. Survival and growth of the *Vibrio* spp. in the aquatic environments and in fish are affected by temperature, besides (sea)water salinity, solar and UV radiations (35).

Coral reefs support about 25% of marine fisheries providing both food and shelter. Over the past few decades coral reefs have declined significantly due to global warming, ocean acidification, invasive species, sea level rise, intense fishing, and other reasons (9). Bleaching occurs when corals, stressed by rising temperatures expel the colourful algae (zooxanthellae) living in their tissues, leaving them white and prone to disease. During 2014–2017, marine heatwaves caused the Third Global Coral Bleaching Event (36).



The adverse effect of temperature can be more intense with respect to tropical as well as sub-tropical fisheries, as these waters have lesser oxygen content. In contrast, Scandinavian temperate waters, particularly the open shelf regions and the Norwegian Sea, are generally characterized by richer oxygen levels due to cold water temperatures and hence protecting underwater life. Tropical regions often experience a loss of species due to elevated heat stress, whereas temperate regions experience increase in diversity due to migration of species. Invasive species compete with native species for space, food and other resources, turn out to be predators for native species and spread diseases (37).

The inland fisheries sector is related to ponds, streams, rivers, lakes, and artificial or modified habitats such as reservoirs and support local livelihoods, economies, and food systems. Most inland fisheries are subject to anthropogenic pressures including over-exploitation of fish, introduction of non-native species, pollution, and habitat degradation. The sector is highly vulnerable to changes due to rising temperature, altered precipitation, and habitat loss, which reduce fish stocks, disrupt breeding, and threaten food security for dependent communities. Increased temperatures reduce dissolved oxygen levels, hindering fish respiration and increasing mortality. Intensified flooding can disrupt spawning and alter migration patterns (38).

2.2.2. Influence on biodiversity. Aquatic biodiversity is sustained across marine (oceans, seas, estuaries), brackish and freshwater (rivers, lakes, reservoirs etc.), and is critical for maintaining habitat-dependent fishery populations. Ocean warming is one of the main drivers of biodiversity loss, resulting in changes in species abundance and their migration from lower latitudes to higher latitudes. Extreme weather conditions can even cause habitat changes especially from low-salinity/brackish waters. The relative abundance of different species shifts in favour of those that are more tolerant of low-oxygen conditions, such as jellyfish and squid. Overfishing and dumping of bycatch along with climate change events



can further damage marine biodiversity (39). Biodiversity loss is emerging risk to global economy as it affects traditional marine resources impacting the livelihood and well-being of coastal fisheries (40). Climate change associated events, briefly discussed above, affect vulnerable and marginalised people, who face depleted fish stocks and are unable to change fishing gear or travel further for fishing (<https://unstats.un.org/sdgs/report/2025/Goal-06/>, accessed, 24 August 2025).

2.2.3. Influence on aquaculture. Aquaculture plays a major role supporting commercial fisheries to provide food security, nutritional wellness, sustainability and economic progress, making farming an essential component of modern food systems. Farming is widely distributed across freshwater, marine, and brackish waters under tropical, subtropical, and temperate climate. Finfish and crustaceans are mainly produced in tropical regions, followed by subtropical regions, and much less in temperate regions. Aquaculture will remain the main driver of growth in fisheries and aquaculture production, which is projected to reach 212 Mt by 2034 (2). However, global warming related changes in water quality parameters, including pH, salinity, dissolved oxygen, and eutrophication can become health stressors in aquaculture. These can lead to losses of production and infrastructure arising from extreme events such as floods, increased risks of diseases, parasites and harmful algal blooms. Impacts also include reduced availability of wild seed as well as reduced precipitation leading to increasing competition for freshwater (41) (42). Recently, detailed studies were undertaken to evaluate temperature effects on growth of white leg shrimp (grown at 29° to 40° C), giant tiger prawn (35° C); kuruma prawn (36° C); the giant freshwater prawn (33° to 38° C); green mud crab (32° to 37° C); lobsters (23° to 32° C), Australian freshwater crayfish (30° to 38° C), and many others. The results showed that rising temperatures caused increased oxygen demand, reduced immune responses, higher disease risks, impaired growth, faster moulting cycles, and higher mortality. Temperature-induced stress altered feeding



behaviour, antimicrobial resistance increasing the susceptibility to temperature of farmed crustaceans to disease outbreaks. Ocean acidification and salinity changes negatively influenced growth, structural formation, tissue formation, reproduction, shell calcification, reducing survival rates of some species (43). Environmental factors, including water temperature and quality, play crucial roles in the dynamics of microbial pathogens, and climate change is expected to exacerbate disease outbreaks (44). Global warming can adversely affect availability and prices of fishmeal and fish oil, the key ingredients in aquafeed (8).

2.3. Pollution and other environmental pressures

The quality of water from ocean, river, ponds, lakes, estuarine, and other bodies has been deteriorating due to nutrient inflow, organic input, oil spill, toxic chemicals, radioactive materials, hazardous chemicals, and other pollutants caused by anthropogenic activities. Plastics, crude oil spills, heavy metals, sewage and leakage of nutrients are the major pollutants that affect marine and freshwater ecosystems. Rain-induced leaching of methane, amines, ammonia (NH₃), hydrogen sulphide (H₂S), and others from landfilled, putrefied fishery waste and also effluents from aquaculture cause substantial environmental externalities. In recent times, plastic pollution has escalated to an alarming level posing a direct threat to aquatic life and marine biodiversity. Currently only 9% of annual plastics production of 460 Mt is recycled; the rest enters the environment, particularly the ocean (<https://www.globalplasticaction.org/globalplasticstreaty>, accessed March 12, 2026). The most common plastic pollutants are polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), polyurethane (PU), polyethylene terephthalate (PET) and polypropylene (PP). Pollution is also caused by abandoned, lost, or discarded fishing gear, also known as 'ghost gear', which makes up around 10 to 20 percent of global marine plastic. The enhanced production and indiscriminate use of plastic products have resulted in the emergence of



microplastics (MPs) as a new class of pollutants. MPs, measuring less than 5 mm, constitute a major biodiversity hazard to fish, crabs, mussels, and other benthic organisms, as these particles are bioaccumulated in skin, gills, stomachs, liver, intestine, and muscles.

Subsequently MPs reach humans via the food chain. The contents of PE and PP based microplastics in 30 commercially important fish species were 37.5 and 27.2 percentage, respectively (45). Ingestion of MPs can reduce fish growth, leading to reduced biomass. Furthermore, consumption of MPs-contaminated fishery products can cause health risks to consumers due to pollutants such as heavy metals, pesticides, and oil compounds carried by the MPs. This calls for urgent actions to protect the ecosystem integrity from adversaries of microplastic pollution (46).

2.4. Loss and wastage of fishery resources

Food loss and wastage (FLW) occur at all levels of food production including fisheries and aquaculture. It is estimated that for each tonne of seafood consumed an almost equal amount is discarded as waste (1). While bycatch fish constitutes a major loss, 7 to 10 Mt of commercially important species are also discarded during pre-processing operations intended for developing chilled, frozen, smoked, dried, fermented, marinated and other product (European Commission, 2019, https://oceans-and-fisheries.ec.europa.eu/fisheries/rules/discarding-fisheries_en, accessed on 5 June 2025). These discards, also referred as side streams or rest raw material, include heads, viscera, skin, bones, scales, exoskeletons, pens, ink, carapaces, legs, residual meat, shells, and others. Along highly diverse supply chains, the world lost around 23.8 Mt of edible aquatic food in 2021, representing 14.8 percent of total production (26). The amounts of discards, however, depend on the fishery item and process operation. Discard volume can be as high as 50 to 70 percent of whole tuna during canning operation, 40 to 60 percent of whole shrimp, and about



85 percent of crab. Besides the solid discards, seafood processing also releases voluminous amounts of effluents, rich in proteins, lipids and other nutrients (47). Losses of these discards and process effluents are major challenges to nutrition, environment, economic and social development and hence sustainable fisheries (48). The protein rich waste also contributes to climate change and other environmental boundaries, such as nitrogen and phosphorus cycles, global freshwater use, change in land composition, chemical pollution, and biodiversity loss (49). Landfilling, dumping and incineration of the discards and effluents result in putrefaction and emission of GHGs, while the released hydrogen sulphide, ammonia, methane, nitrous oxide, and other gases also have adverse effects on living systems (50). The net effects of depletion of fisheries are economic setbacks including increased food prices, loss of livelihoods, and environmental costs. Table 2 summarizes impacts of various challenges on sustainable seafood production.

3.0. Conventional practices for sustainable fisheries in briefs.

Conventional sustainability practices focus on habitat conservation, control of overfishing, establishment of marine-protected areas, adoption of ecosystem-based management, fish catch limits, size exclusion criteria, aquaculture, traceability, certification programmes, and waste management, all capable for capacity building for sustainable production of the food system. The Code of Conduct of Responsible Fisheries of the FAO, perhaps, is the first major attempt to set out principles and international standards for responsible fishing practices aimed at health of the ecosystem. The Code takes into account the biological characteristics of the resources, their environment and the interests of consumers benefit to retain larger size fish (51). Management rules relate to landing obligations, catch limits, tracking and detecting of illegal fishing vessels, minimum fish size, fish quota including transferable quota and others to prevent overexploitation (52). Imposing



catch limits, quotas and related measures has rebuilt Pacific bluefin tuna fisheries (Waycott, B., Responsible Seafood Alliance, www.globalseafood.org/, accessed, 3 March 2025).

Marine Protected Areas (MPAs) and Exclusive Economic Zones (EEZs) in the ocean restrict anthropogenic activities. The MPA Guide is a framework that enables smart planning, design, and evaluation of new or existing MPAs by providing scientific, societal, and policy priorities to achieve biodiverse and healthy ecosystems (53). As of May 2024, there were 18,200 MPAs covering over 29 million square kilometres of the ocean. At present only 2.7% of the ocean is highly protected. However, protecting just 5% more of the ocean could boost fisheries by as much as 20% (Bryce, E., October 30, 2020, <https://www.anthropocenemagazine.org>). Detailed management interventions with respect to about 300 fisheries around the world resulted in lowered fishing pressure (54). Co-operative efforts between communities, governments and stakeholders maintain the long-term viability of fishing populations, preserve marine biodiversity, and support the well-being of present and future generations (57).

Landings of bycatch fish can be reduced employing by-catch reduction devices such as Turtle Excluder Devices (TEDs) in nets, changing hook/net designs such as square mesh cod ends, sieve Net, FishEye, use of acoustic alarms, etc. These strategies promise to achieve ecological and socioeconomic objectives (58, 59). The species characterisation of bycatch provides information for the design of modified nets (17). Bycatch management devices are useful for targeted industrial trawling in Scandinavian waters having abundance of cod herring, salmon, etc, with low fish diversity. However, in tropical and sub-tropical fisheries, which have high diversity of species, gear designed for one species may catch other species, limiting success in bycatch reduction. In India netting of juvenile fish has been prohibited, stipulating a minimum legal size (MLS) of the fish caught. The MLS values are 50, 29, 9-11, and 7 cm for tuna, catfish, prawn, and, crab, respectively (ICAR-CMFRI, India,



<https://www.cmfri.org.in>, accessed September 25, 2025). Fish Excluder cum Shrimp Sorting Device (JFE-SSD) is a BRD, developed by ICAR-CIFT, India. Designed for tropical trawlers, it reduces catch of juvenile fish and non-targeted species by up to 43% while retaining high-value shrimp and large finfish (55). View Article Online
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Device (JFE-SSD) is a BRD, developed by ICAR-CIFT, India. Designed for tropical trawlers, it reduces catch of juvenile fish and non-targeted species by up to 43% while retaining high-value shrimp and large finfish (55).

Industrial fishing of threatened fish and invertebrates should be reduced for conservation and sustainability commitments (11). Cut-away top belly, short belly trawl and high opening bottom trawls are other designs for selective trawling (55). Selection of gear types is influenced by targeted species, catch potential, resistance offered by gear materials, environmental impact, operational functionality, regulatory performance, among others. The American lobster and Jonah crab dominate New England waters within the trap/pot fishery, while New England gillnet fisheries target groundfish like Atlantic cod, haddock, pollock, flounder species, monkfish and elasmobranchs. A gear-based management index (GBMI) for coastal and offshore fisheries provides information for improving selectivity, promoting gear substitution, preventing gear loss, and enhancing crew safety. The method entails proactively halting destructive fishing practices ensuring the long-term health of marine resources (56). These aspects have been in the Skippers' Guidebook to Sustainable Purse Seine Fishing Practice. (<https://www.iss-foundation.org/>, accessed 27 April, 2026). The small-scale fisheries (SSF) Voluntary Guidelines are intended for securing sustainable SSF in the context of food security and poverty eradication (20). Evaluation of 86 multi-species models helped understanding of sustainable production based on population dynamics, growth rate, mortality, biomass, trophic interactions, and other ecological dynamics (81).

Rejuvenation and restoration of coral reef is important to support sustainable fisheries by rebuilding crucial habitats, biomass, and biodiversity for food security. The restorative plan includes reducing pollution, stopping overfishing, and selective breeding of corals which can increase reef health and improve the resilience of reefs. Introducing specific species, like



herbivorous fish, helps control algae and restore ecosystem function speeding up recovery

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(60). The reef locations with the greatest potential for sustainable gains are among those with the greatest food and micronutrient deficiencies (61). Artificial reefs are human-made underwater structures, such as sunken ships or concrete modules, designed to mimic natural reefs, enhancing biodiversity, supporting fishing, and driving tourism (62). Mangroves, the wetlands between the coast and mainland are the primary sources of livelihood for coastal communities. There is a need to reduce impact of aquaculture on mangroves, salt marshes, and seagrasses. Planting of fast-growing mangrove trees can control climate-induced sea level rise, protect fishing zones and minimize vulnerability in coastal regions (www.oneearth.org, accessed January 15, 2026, accessed 5 June 2025).

A number of international efforts have been initiated to protect the ocean and support sustainability, some of which are mentioned below. The Ecosystem-Based Fisheries Management (EBFM), collectively considers species, habitats and human activities in marine ecosystems (<https://www.fisheries.noaa.gov/>, accessed 16 March 2026). The Great Blue Wall Initiative, endorsed by the World Conservation Congress, is an African driven initiative for nature-based recovery through the establishment of a transformational movement across MPAs in the Western Indian Ocean (WIO). Its three-point agenda include strengthening biodiversity, climate resilience and socio-economic development across the WIO by 2030 (<https://iucn.org/resources/brochure/great-blue-wall-initiative>, accessed February 12, 2026). The Asia-Africa BlueTech Superhighway (AABS) project supports sustainable fishing of the Zanzibar island (worldfishcenter.org, accessed February 10, 2026). Catch limits, quotas and related measures have helped rebuild Pacific bluefin tuna fisheries (Waycott, B., Responsible Seafood Alliance, www.globalseafood.org/, accessed, 3 March 2025). The International Pacific Halibut Commission has its agenda for marine conservation in the context of global events and trends in fisheries management. The Commission implemented a wide range of



conservation measures (82). Illuminating Hidden Harvests' (IHH) is a collaborative study that provides a 'snapshot' of the current contributions, impacts and drivers of change of small-scale fisheries on a global scale (<https://worldfishcenter.org/>, accessed 5 March, 2026). The International Seafood Sustainability Foundation (ISSF) is committed to tuna conservation and sustainable use of tuna fisheries through science-based practices. Its agenda also include marine ecosystem health, bycatch reduction, prevention of illegal and overfishing and others (<https://www.issf-foundation.org/>, accessed 27 April, 2026). The Kunming-Montreal Global Biodiversity Framework (GBF) addresses biodiversity health by saving endangered species, mitigating impacts of invasive species and minimizing climate crisis (1) <https://www.unep.org/resources/kunming-montreal-global-biodiversity-framework>, accessed 1 May, 2026) The European Commission proposed the Nature Restoration Regulation Law to address biodiversity loss and to protect and restore the habitats for sustained recovery of biodiverse fish and shellfish (<https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030en>, accessed March 10, 2025). During the period 2022-23 more than 20,800 Marine Stewardship Council (MSC) certified sustainable fish and seafood products were on sale around the world (<https://www.msc.org/what-you-can-do/eat-sustainable-seafood/fish-to-eat>, accessed August 24, 2025). The Bio-Based Industries Joint Undertaking (BBI JU) encourages green transition of waste streams from agro-food industry into bio-based value-added products through state-of-the-art technologies (83). In the U.S., Fishery Management Councils (FMCs) are responsible for developing plans to optimize yield for each fishery on an ongoing basis, which also involves climate-ready fishery management (80). Table 3 summarises key climate strategies for fisheries and aquaculture.

The conventional practices intended for fisheries sustainability have limitations since they often fail to achieve long-term results due to their general focus on short-term economic



gains, limited scientific data, and weak enforcement mechanisms. Major limitations arise due to limited success in making ecosystem-level impacts, the challenges of managing migratory fishes and others. Most practices focus on a single species rather than the broader ecosystem, ignoring the complex interactions among the flora. Overexploitation by many fisheries indicates failure of current approaches to fisheries management. A large proportion of global fisheries, particularly in developing nations, lack proper stock assessment information, leading to poor management. . Allocating fish quota is a hotly disputed issue across the world (52). These setbacks result in unknown damage to ecosystems calling for integrated multi-disciplinary measures

4.0. Blue transformation to address sustainability challenges

The challenges facing blue food production, briefly pointed out, call for innovative and adaptative measures with a view to achieve global food security. The term ‘food transformation’ was suggested by the United Nations Food System Summit in October 2021, which asked “set the stage for global food systems transformation to achieve the Sustainable Development Goals by 2030” (<https://www.un.org/en/food-systems-summit>, accessed January 2, 2026). The FAO in 2021 launched ‘Blue Transformation vision’ to use existing and emerging knowledge, tools and practices to secure and sustainably maximize the contribution of aquatic food systems to food security, nutrition and affordable diets. The FAO vision proposed a set of three Action Plans under ‘*Blue Transformation in Action*’ to build sustainable, resilient, gender-responsive and inclusive fisheries and aquaculture. The Action Plans have objectives, namely, (i) effective management to conserve all fisheries and ensuring healthy stocks, (ii) sustainable aquaculture expansion and intensification to meet global demand while ensuring equitable distribution of benefits, and, (iii) upgrading aquatic value chains that guarantee social, economic and environmental sustainability of the food systems (1). The key operations to achieve the objectives involve to mapping resources,



implementing nature-based practices, diversifying production, developing value-added products, market studies, among others. The transformation protocols, which are mostly science-based, turn the supply chain sustainable while meeting legal and ethical standards for welfare of people, animals, and environment. Cutting-edge technologies on these lines can offer triple benefits, namely, protection of biodiversity, boosting fisheries yield and securing marine carbon stocks that are at risk from human activities (6). Achieving these objectives generally requires integrated, multi-disciplinary approaches.

4.1 Importance of integrated multi-disciplinary measures

In modern times, multi-disciplinary approaches bring together expertise derived from different professional fields that provides a more comprehensive and holistic outcome than a single discipline in solving a particular problem. Integrated environmentally, economically and socially sound practices are able to safeguard aquatic ecosystems against challenges of stock depletion, global warming, environmental changes, habitat destruction, among others with a view to achieve sustainable production. The multi-disciplinary approaches rely on biological, electronic, economic and social science data for decision-making. Prioritising actions that not only produce more seafood, but consider aspects of access and utilisation for people affected by food insecurity and malnutrition is an essential part of designing future sustainable and secure seafood systems. The data generated encompass areas such as stock assessments, harvest levels, bycatch species, population patterns, environmental changes including the effects of global warming, migration of species, and others (63, 64).

Recent times have seen interesting roles of fourth industrial revolution (Industry 4.0) innovations such as smart sensors, big data, artificial intelligence (AI), Internet of Things (IoT), and others in sustainable food production systems. Automation enables real-time monitoring of animal behaviour, optimization of feeding, water quality, and early detection of system anomalies, thereby identifying technology options and energy efficiency



improvements to help resilience and sustainability (65). Blockchain technology is used to record every step from harvesting, processing, packaging, shipping, and retail in the seafood supply chain allowing sustainable development including fair trade practices in the industry. The advantages encompass improved data efficiency, optimised decisions for sustainable practices, and streamlined integration across the seafood supply chain (66). The AI-powered tool, *SmartCatch*, can detect species, size and weight, supporting faster and more accurate data collection even in areas without reliable internet (<https://smart-catch.com/>, accessed March 2, 2026). High-tech bycatch reduction devices are available deploying data analytics, remote-control and camera-enabled lights and sensors, trained by AI (Miller, A., Global Seafood Alliance, 12 June 2023, accessed 17 February, 2026).

Seafood traceability is the process of tracking seafood from catch or farm to final sale, recording data including species, origin, their genetic nature, processing methodology, and handling. Traceability improves supply chain oversight and delivers healthy and responsible seafood products to markets. It also addresses growing pressure from regulators and buyers demanding greater transparency. Seafood traceability can take advantage of the rapid digitalization and technological advances to support compliance with international regulatory standards through detecting fraud by ensuring that the seafood supply chain is authentic, ethical, responsible, safe and sustainable, that also builds consumer trust in the seafood supply chain (67). The ‘Global Dialogue on Seafood Traceability’ (GDST) is dedicated to creating and sharing a common language for traceability in the seafood supply chain (<https://thegdst.org>, accessed March 10, 2025). The National Framework on Traceability in Fisheries and Aquaculture of the Department of Fisheries, Government of India integrates digital tools like blockchain IOT, QR codes and GPS to track seafood products from ‘farm to plate’. It covers the entire value chain, including fishing vessels, aquaculture farms, processing units, and supply chains, aiming to scale up seafood exports, improve food safety



and enhance market access (<http://dof.gov.in>, accessed January 2, 2026). Electronic solutions are being used to report catches and track small-scale fisheries to control IUU fishing and for improved product traceability (Global Seafood Alliance, <https://www.globalseafood.org/>, accessed 20 June, 2025). Protecting just 5% more of the ocean could boost fisheries by as much as 20% (Bryce, E., October 30, 2020, <https://www.anthropocenemagazine.org>).

4.2. Mitigation of hazards of global warming. Climate action measures are able to transform and reorient fisheries systems to support food security, protect marine biodiversity, and ensure sustainability. Delay in addressing climate eventualities seriously affect marine conservation and health of the seafood industry (68). Decarbonization is at the centre of measures for the reduction of environmental pressures on the ecosystem with a view to limit global warming to below 1.5 °C above preindustrial levels. CO₂ capture, utilization, and sequestration (CCUS) actions for decarbonization include conversion of CO₂ into fuels, chemicals, minerals, and sequestration. The United Nations Framework Convention on Climate Change (UNFCCC) recognized the importance of aquatic foods in providing critical climate solutions (1). Currently CCUS technologies are at different stages of development and deployment (69). Policy options for climate solutions with respect to capture fisheries include development of sustainable and climate adaptive management, reduction of emissions from fisheries and support of climate adaptive practices for fishing communities (26). Ocean-based climate actions can reduce up to one-fifth of the annual GHG (www.oceanpanel.org, accessed March 22, 2025).

4.2.1. Energy transition to reduce fishing-related carbon footprints. Fuel use by fishing fleet is the major factor influencing cost of production of capture fisheries. Rise in fuel prices due to geopolitical conflicts and other reasons adversely affect fishing activities. Global fishing fleets, powered by diesel are also responsible for an annual carbon emission up to 159 Mt, contributing to global warming. Therefore, environmentally friendly alternate fuels



are required for cost reduction of fishing operations and to reduce fishing related anthropogenic GHG emissions (16).

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Phase-out of fossil fuel along with transition to bioenergy can be critical tool in this regard. Bioenergy can meet climate resilience and energy security, providing cleaner air. The voluminous fishery discards released by the industry stand out as the most readily available source of biofuel. Lipids-rich fishery waste biomass presents a viable pathway towards energy security. The benefits of biofuel from fishery waste biomass are its low-cost, readily available nature, waste reduction through its biotransformation, energy security and lowered GHG emissions (70). Anaerobic digestion and enzymatic hydrolysis are commonly used to produce bioethanol, biogas, and other biofuels from the waste biomass (71). Shrimp shell could yield a maximum of 89 percent biodiesel at an oil to methanol molar ratio of 1:12 (72). Fish waste oil, when blended with conventional diesel, can improve engine thermal efficiency and reduce hydrocarbon emissions (73). Recently, a method to harness bioenergy from seafood-related process effluents has been suggested using microbial fuel cells. The treatment also allows prospects of sustainable wastewater management (74).

The use of liquid natural gas (LNG) and biogas can contribute to seafood sustainability (75). LNG along with High-Speed Diesel (HSD) could be a cleaner and technically viable dual sustainable fuel system for marine fishing vessels. LNG can substitute HSD up to 24 percent for up to 30 percent reduction in fuel costs and emissions. This could reduce global warming and ocean acidification in the range of 19 to 24 percent, as assessed by Life Cycle Assessment (LCA) (76). An energy-efficient, multi-purpose green fishing vessel for deep sea fishing operations has been developed by ICAR-CIFT, India (55). The Small-Scale Fisheries Sustainability Suite, developed by WorldFish, supports decision-making in SSF with respect to reduction of fuel use and protection (www.worldfishcenter.org, accessed 28 August, 2025).



Apart from eco-friendly fuels, climate-savvy engines, improved vessel shapes, etc. can build resilience and adaptive capacity. Energy efficient, right-size engines reduce fuel consumption by as much as half, while optimizing gears reduce emissions by more than half. These strategies reduce energy use and minimise emissions from fishing fleets (55). Multi-disciplinary actions have good scope for cost reduction as well as GHG reduction. Prioritizing low-fuel gears within each fishery reduces GHG emissions up to 61 percent, depending on the species. Green technologies such as battery systems, electric engines, and gas tanks, along with additional cargo space, can be a plausible option to reduce GHG emissions (77). Solar panels can reduce carbon footprint of aquaculture operations. Use of solar photovoltaics (PV) can be practical in agri-food systems including farming operations to reduce carbon footprints of (IRENA, <https://coalition.irena.org>, accessed March 12, 2026). . Exploitation of the energy potential of tides, currents, sun light, waves and wind can be interesting future options to reduce emissions associated with fisheries operations (Pillai, A. K. B., <https://www.academia.edu/s/41b8df7d02#>, accessed January 23, 2026). There is insufficient data on fuel use across the diversity of small-scale fishing operations to reliably estimate emissions (28).

Climate change mitigation practices such as reducing energy consumption, and use of alternate energy have shown potentials to moderate decline in marine animal biomass in the Pacific, Atlantic, and Indian Ocean basins (29). The benefits relate to conservation of natural marine resources, emerging fisheries, future planning, integrated monitoring, development of climate-resilient MAPs and others to make the industry environmentally, socially, and economically sustainable (78, 79, 80). The Arctic council is addressing the climate crisis through coordinated research, policy development and international cooperations (<https://arctic-council.org/>, accessed 21 May, 2025). The Climate-Resilient Fisheries Planning Tool of the Fishery Solution Centre guides users to assess and protect



climate resilience through climate vulnerability assessment and innovative technologies to

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improve climate resilience with respect to their fishery

(<https://fisherysolutionscenter.edf.org/>, accessed 5 December 2025).

4.2.2. Transformative actions to control pollution: Plastic pollutants can be transformed by these materials into environmentally friendly products such as paving blocks and also as materials for road construction. Possibilities of making comparable products from abandoned fishing gear can also reduce pollution. An inclusive treaty can set global standards, protect ecosystems, human health, and livelihoods

(<https://www.globalplasticaction.org/globalplasticstreaty>, accessed March 12, 2026)

Recently, a simple and interesting solution to reduce both plastic waste and CO₂ emission has been suggested. This involves repurposing polyethylene terephthalate plastic waste to capture CO₂ through aminolysis reaction. The reaction products, a bis-aminoamide (BAETA) and oligomers, could capture appreciable amounts of CO₂ thereby addressing both plastic waste and CO₂ emissions (84). An eco-friendly approach to produce hydrogen from fishing net waste (ghost gear) has been reported. The production of H₂ was increased by pyrolysis of the waste under CO₂. Feasibility of the process was confirmed by techno-economic analysis (85).

In collaboration with tuna skippers, ISSF identifies best practices for building, deploying, tracking, and recovering FADs to prevent marine debris and ghost fishing (<https://www.issf-foundation.org/>, accessed 27 April, 2026).

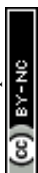
4.3. Sustainable aquaculture

Aquaculture is at the forefront of initiatives to transform fishery food systems for sustainable production. Enhancing climate forecasting, promoting sustainable practices, and fostering international policy alignment are crucial for ensuring the long-term sustainability of the aquaculture sector in the face of evolving climatic challenges. Nature-positive,



transformatory cultivation conditions contribute to sustainable, healthy, nutrient-rich fishery products in sufficient quantities to meet global goals of food security (3). As aquaculture expands, strategic planning, investment, and resilience-building measures are essential to reduce emissions as well as vulnerability of farming activities to climate change. Policy options call for climate-adaptive technologies and practices to increase aquaculture's resilience to climate change that can also minimize threats from emerging diseases (26) (86). Salient measures to address include leveraging genetics and biotechnology, employing innovative management and engineering solutions, improving information systems, and strengthening governance frameworks (41). In-depth understanding of influence of elevated temperatures on growth performance and physiological responses of aquatic species on food intake, moulting, immune response, survival, genetic selection, and ecosystem-based policies have significant potentials to optimize production (43). Although a wide variety of freshwater, brackish water and marine fishery items have shown amenability to aquatic environments, most countries limit farming to a few popular species. For example, in India, aquaculture is concentrated to three major carps viz., rohu (*Labeo rohita*), catla (*Catla catla*), mrigal (*Cirrhinus mrigala*), and the giant freshwater prawn (*Macrobrachium rosenbergii*) (78).

4.3.1. Farming technologies. Sustainable aquaculture has attracted novel transformative farming technologies in recent years. These options supported by biotechnology, genetics and nutrition, along with innovative management, engineering solutions, and frameworks can improve resilience of aquaculture while minimizing environmental hazards. Recirculating aquaculture systems (RAS) is an intensive approach to fish and shrimp farming, and enabling high-density production under precise environmental control. The water used in the farm is treated by filtration before being recirculated among the culture tanks thereby minimizing water use. Apart from reduced water consumption, other advantage of RAS is higher



productivity. Renewable energy together with process integration and advanced monitoring can offer additional benefits (87). RAS technology for the production of popular farmed fish species such as Atlantic salmon, European seabass, gilthead seabream, yellowtail kingfish, arctic charr and rainbow trout has been discussed (88). Bio-floc technology (BFT) is a system where probiotic microorganisms at optimal carbon to nitrogen ratio convert fish waste and unused feed (generally rice bran and molasses) into protein-rich fish feed. Symbiotic system combines fish farming with plant cultivation where fish waste provides nutrients for plants and plants purify water for fish. This sustainable close loop approach reduces waste and resource utilization. Pimentel et al (2025) recently compared RAS, BFT and Symbiotic systems for the cultivation of *P. vannamei* in terms of water quality, plankton composition, and growth in low salinity (2 g per L) and high stocking density (500 shrimp m⁻³) for 30 days (89). The shrimp were stocked at a mean weight of 1.27 ± 0.06 g. In the BFT, dextrose was used as the organic carbon source and administered at a carbon: nitrogen ratio of 15:1, while in the Symbiotic, rice bran processed by probiotic microorganisms was used as an organic fertilization strategy. In the RAS treatment, all nitrogen species remained stable throughout the trial with ammonia and nitrate concentrations lower than that of BFT and Symbiotic. The authors concluded that the Symbiotic system could be an alternative for super-intensive culture of the shrimp in low salinity water (89). The Integrated Multi-Trophic Aquaculture (IMTA) is a circular economy model, where growing different aquatic plants and animals together make farming more sustainable and efficient. IMTA reduces environmental impact, enhances resilience, provides economic and social benefits, particularly in the case of bivalve aquaculture (90). Aquaponics combines RAS with hydroponics. In this system, the metabolized products obtained via microbial conversion and biodegradation of aquaculture waste serve as nutrient sources to fruit or vegetable plants in the hydroponics unit (91). The Pacific oyster (*Crassostrea gigas*) has been suggested the most widely farmed oyster species



worldwide, as it exhibits rapid growth, strong tolerance to environmental stress, negligible GHG emission and substantial economic value. Its productivity can be regulated by water flow velocity and variations in pH values, underscoring the potentials of hydrodynamic management for sustainable production (92). Farming of Irish Pacific oyster (*Magallana gigas*) has relatively low environmental impacts (373.86 kg CO₂ eq. per tonne), compared to other cultivated seafood items. One ton of oyster can remove, on an average, 3.05 kg of nitrogen, 0.35 kg of phosphorus and sequester 70.52 kg of carbon from the environment, making oysters a sustainable blue food with environmental benefits (93).

Cage culture using floating, submerged, or fixed cages allows rearing fish in natural marine environments, coastal waters, or bays. It enables high-density, scalable production with low capital, utilizing natural currents for oxygenation and waste removal, making it ideal for species like seabass, groupers, snappers and giant trevally (55). Mariculture has potentials to decrease carbon footprints up to 40 percent in comparison with freshwater aquaculture. Adoption of mariculture alongside freshwater aquaculture could offer considerable climate benefits (94). Mussels play a vital ecological role as filter feeders, improving water quality, and are economically important in aquaculture. Their global distribution and ecological significance underscore importance of mussels in aquatic ecosystems. Marine mussel farming is sustainable having potential in enhancing global food security (95). The Climate-Adaptive, Inclusive, Nature-based Aquaculture (CAINA) project led by *WorldFish* in partnership with Malaysian universities is designed to support sustainable aquaculture that is gender equitable and socially inclusive. The project seeks to explore how public and private investors can be effectively aligned to drive the aquaculture sector toward greater sustainability and profitability (Allison, E. et al., worldfishcenter.org, accessed February 10, 2026). Environmental DNA (eDNA) techniques have emerged to detect numerous current species simultaneously, avoiding the requirement for direct fish



tissue collection by focusing on the residual DNA and waste products of metabolism left behind in their surroundings (57). View Article Online
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4.3.2. Novel aquafeeds. In 2034 fishmeal and fish oil are projected to represent 83% of the 21 Mt live weight of fish and other aquatic products for fish feed production (2). Such heavy uses of fishmeal and fish oil for aquafeed development pose sustainability concerns.

Therefore, novel feeds are being developed, which are essential to reduce GHG emission, expansion of integrated low input, and other practices for resilience of aquaculture (9)

Selective breeding, genetic improvements and high-quality feeds can improve feed conversion ratio, reducing wastage as well as costs, while minimising environmental impacts (28). Although gains have been noted in recent times in aquaculture feed efficiency, the

dependence on marine ingredients persists. Further, reliance on ingredients from terrestrial sources has increased (96). Shrimp hydrolysate is sought after by aquafeed and petfood

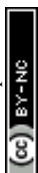
industries and is a beneficial ingredient in aquafeed for its bioavailability, palatability and immune resistance enhancing properties (97). Insects such as black soldier fly as a potential

protein source to sustainable feed systems has been recognized. Marine microalgae offer a promising alternative due to their comparable nutrient profiles and potential for large-scale, sustainable production. Diets formulated with defatted protein-rich or DHA- and antioxidant-

rich microalgae, combined with oil such as canola oil can viably replace fish meal and fish oil without compromising fish performance, nutritional quality, or production economics.

Microalgal co-products can fully replace fishmeal as feed for trout while maintaining fish performance, flesh composition, and cost-effectiveness. Incorporating taurine and lecithin in the feed enhanced palatability, feed intake and fish growth (98). Single cell proteins (SCPs), developed by cultivation of bacteria, yeast or algae in media containing nutrient-rich seafood discards and other biowaste, can be sustainable and environment-friendly aquafeed (99).

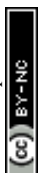
Seafood waste can be recycled and formulated into nutritive feed pellets for freshwater



fish species, such as grass carp, grey mullet, and tilapia (100). Crustacean processing side streams, especially shrimp head and shell, can be another raw material for aquafeed (101). Tuna by-products can be potential protein and lipid sources in the feed and therefore feed development is a sustainable alternative to traditional disposal methods of the discards (102).

Phototrophic bioconversion of aquaculture sludge by anoxygenic phototrophic bacteria (APB) minimizes carbon and nutrient dissipation; the assimilated protein-rich biomass can be utilized as aquafeed. This requires pre-treatment to solubilize aquaculture sludge to obtain bioavailable substrates(91). The enhancement of aquaculture effluents and biomass for uses such as aquaponics, hydroponics, algae cultivation, daphnid co-cultivation, and biofertilizers presents opportunities for nutrient recovery while ensuring that non-toxic wastewater can be safely discharged into external water bodies. This approach can also revolutionize wastewater treatment, shifting the economic model of wastewater management from a linear system to a circular, more sustainable one (103). Benefits of microbial bioremediation of waste water generated from constructed wetlands, ecological floating beds, RAS, BFT, aquaponics system, and (IMTA) have been pointed out (104). Although technologies, such as RAS, integrated aquaculture–agriculture (IAA), Biofloc systems and solar powered hatcheries have been promoted as climate smart solutions, limited evidence exists on their comparative performance. Recently, a Climate Smart Technology Index (CSTI) was formulated integrating four weighted performance pillars, namely, productivity, resilience/adaptation, mitigation/environmental performance and socio- economic inclusivity. The studies showed that RAS had the highest composite CSTI score (0.76), followed by Biofloc systems (0.73), IAA (0.71), and cage culture (0.67) (105).

Precision aquaculture is advanced technology using sensors and digital technologies for optimal production (106). The IoT-based water quality monitoring system that measures



pH, temperature, and turbidity sensors boosted productivity of lobster farming (107). AI-powered cameras and advanced sensors enable precise, real-time oversight of fish health and environmental conditions to prevent stock losses for higher yields (Global Seafood Alliance, <https://www.globalseafood.org/> 5 June 2025, accessed 30 June, 2025). Increasing complexity in managing ecological sustainability, disease control, production efficiency, and supply chain resilience presents ongoing challenges of aquaculture. To address these, complex network analysis (CNA) has been applied to explore interactions among fish species, farms, environmental factors, and stakeholders. Future research directions include developing dynamic network models, improving interdisciplinary data integration, and applying machine learning techniques to enhance analytical capabilities (108). AI assisted feeding and monitoring improves feed usage 15 to 20 % and cut labour by 25 to 30 % (109)

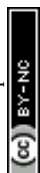
Intensification of aquaculture practices may lead to diseases caused by bacterial pathogens such as *Vibrio* spp., *Aeromonas* spp., and *Streptococcus* spp., and also viral, fungal, and parasitic pathogens. Scientific innovations like probiotics, vaccines, RNA interference, responsible antibiotic use, and water quality management have scope to prevent diseases in aquaculture (44). A comprehensive understanding of the gut microbiota in the health of white leg shrimp, *L. vannamei*, can be critical for sustainable shrimp aquaculture industry (110). The emergence of antimicrobial resistance in aquaculture is a concern, driven by antibiotic overuse (96). Functional dietary supplements including probiotics and prebiotics are recommended as safe and sustainable alternatives for antibiotics in aquaculture (111) (112). The global information system on aquatic genetic resources (AquaGRIS) provides information on existing farmed types and wild stocks of aquaculture species (1). Guidelines for Sustainable Aquaculture (GSA) present a comprehensive and adaptable framework to support sustainable aquaculture expansion and intensification (WorldFish, worldfishcenter.org, accessed March 20, 2025). The Global Salmon Initiative



(GSI) is a collaborative effort committed to driving climate resilient global salmon farming that supports sustainable food systems with lowest environmental impacts (<http://globalsalmoninitiative.org>, accessed 18 December, 2025). Ready-to-adopt technology packages for seed, feed, fishery health, for freshwater, marine, and aquaculture in open water are available (113). Certification programs and robust regulatory policies are essential to standardize practices and foster sustainable aquaculture (114). New technologies supported by science-based innovations and digital devices have increased sustainable culture of Nile tilapia and penaeid shrimp (115). Genetically Improved Farmed Tilapia (GIFT) is fast growing freshwater fish adaptable to a wide range of environments to provide a sustainable nutritive food (Mohamed, E. Y., A "GIFT" for sustainable aquaculture that's reaping benefits worldwide, www.worldfishcenter.org, accessed March 20, 2025). It has been forecast that sustainable aquaculture production is expected to grow at least by 35 percent by 2030, especially in food deficit regions. Growth in the sector creates employment and skills that improve income and livelihoods (1). As demand for shrimp grows not only in the food sector, but also in the pharmaceutical, healthcare, and cosmetics sectors, strategies for sustainable shrimp aquaculture have been discussed recently (116).

4.4. Upgrading aquatic value chains - blue transformation of fishery discards

Aquatic organisms are considered part of Mother Nature's medicine cabinet, because these organisms possess a plethora of bioactive compounds having diverse nutraceutical and medicinal activities (117). Seafood waste biomass can be a resource for several nutraceuticals, industrially important compounds including agricultural chemicals, bioplastics, biofuel and others. Therefore, transformation of the waste biomass into highly useful ingredients is economically, socially and environmentally advantageous. The 'trash-to-treasure' conversion strategies involve a combination of processes based on biological,



thermal, chemical, mechanical and physical methods, ideally supported by zero waste and circular economy strategies with a view to maximal recovery of ingredients for optimal resource utilization, the success being dependent on feedstock composition, target products, scale of operation, and economic considerations hazards (118) (119). The transformation approaches allow solutions for the pressing issue of waste management while bolstering both environmental and economic sustainability (120) (121) (122).

The popular biotransformation processes are microbial fermentation and enzyme treatments (123) (124). The fermentation process is an essential part of building secure, safe and sustainable food system (125). Fermentation employs aerobic, anaerobic, facultative or mixed microorganisms including bacteria, fungi, microalgae, or protozoa. Efficiency of the process is dependent on the nature of the starter culture, pH, and substrate composition. Two popular fermentation systems, solid-state fermentation (SSF) and submerged liquid fermentation (SLF), have emerged for the recovery of proteins bioactive peptides, and amino acids and other ingredients from food waste (126). Applications of fermentation processes allow safe, efficient, and environmentally friendly recovery of valuable ingredients from marine crustacean waste and other fishery discards (127). Demand for specific proteins including enzymes and other food ingredients is driving interest in precision fermentation, which involves use of synthetic biology tools to tailor microbes for process efficiency (128) (Naidu & Audichya, <https://gfi-india.org/fermentation-derived-ingredients-are-powering-the-next-wave-of-alternative-protein-innovation/>, accessed 28 February, 2026).

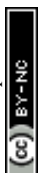
Enzymatic conversion coupled with microbial fermentation under non-thermal processes can be used for efficient recovery of protein, chitin, and astaxanthin from shell waste and other fishery discards (129). Enzymes have established themselves as an effective tool for texture and flavour modulation of food products. Enzymes, particularly proteases and lipases, isolated from seafood byproducts can be used as sustainable solutions to enhance



food flavours, textures, providing greener alternatives to traditional solvent-based methods (130). Cold-adapted marine proteases can convert proteins from biowaste into high-value bioactive peptides and nutraceutical ingredients under low thermal conditions (131). Mechano-enzymology is an innovative green process that employs mechanical force such as ball milling, enzyme reactive extrusion, and sono-catalysis to drive enzyme-catalysed reactions (132).

Non-thermal extractions employing ultrasonic, microwave, pulse electric field, supercritical fluid and others allow optimal recovery of ingredients from aquatic sources (133) (134). A green approach for collagen processing is based on pre-treatment (fermentation, high shear mechanical homogenisation), non-thermal extraction followed by ultrafiltration of the protein (135). Extractions by ionic liquids (ILs), deep eutectic solvents (DESs), enzyme, microwave, ultrasonic and subcritical water treatments enhance extraction efficiency, yield, and purity of ingredients from fishery and other marine waste. Extracted bioactive compounds from fishery discards exhibit considerable potential in addressing major health issues and therefore reduce the burden of the pharmaceutical industry (136). Green and eco-friendly approaches for the recovery of chitin and chitosan from shrimp shells have been discussed. These include extractions by ILs and/or DESs, microbial fermentation, enzyme-, microwave-, ultrasonic-, and electrochemical-extractions (137). Steam explosion and supercritical CO₂ can also extract chitin from shrimp shells (138).

Iso-electric pH solubilization precipitation (ISP) is a plausible method for the recovery of functionally active proteins from protein-rich fishery discards. The process, known as the 'pH shift process', developed by Hultin's group, recovers proteins from fish heads, back-bones, tails, trimmings and also bycatch (139). Flocculation, sedimentation, membrane-based separation, and other processes help recovery of proteins and other ingredients from effluents of seafood processing industries. Recovery of proteins from these



sources reduces carbon footprint favouring a positive impact on several important planetary boundaries (49) (47) (140). Cultivation of microalgae such as *Chlorella vulgaris*, and others in seafood process effluents steers reduction of effluent-related environmental hazards, safe disposal of the liquid waste, restoration of water resources, and the production of valuable products. The cultivated microalgae, designated as ‘single cell proteins’ (SCPs) can have protein contents as high as 80 percent on dry weight basis, besides appreciable levels of carbohydrates, minerals, and vitamins. The recovered microalgal proteins are sustainable alternatives to conventional protein sources in food and biotechnology applications as well as aquafeed development for Pacific white and other shrimp species (99). The microalgal technology is an eco-friendly, energy-efficient solution for transforming industrial biowaste, that can also address environmental sustainability (141).

Advancements in genetic and metabolic engineering have opened up novel avenues for biotransformation of food waste into novel products. The process for cultivated seafood involves harvesting muscle cells from live fish, immobilizing them and allowing to grow in nutrient rich medium under osmolarity conditions, which are comparable to marine habitats. Depending on the cultivation conditions, the products can resemble popular fish such as salmon, tuna, shrimp, crab or mussel with comparable nutritive values, taste and flavour (142). Cell-cultivated seafood also provides options for fortification of fish meat with nutrients such as omega-3 fatty acids and others. Production of alternate seafood as a novel protein source is associated with energy savings, reduced GHG emissions, environmental and other benefits (143). A roadmap for cell-cultivated aquatic food products as a mainstream food source has been discussed (144). The catch of popular wild bluefin tuna is affected by overfishing, supply volatility, and concerns about mercury. Cultivated bluefin tuna aims to address some of the challenges facing its ocean-based counterpart (Cultivated bluefin tuna is good for health and the high seas - Future of Foods Interviews, Gordon Research



Conferences, San Francisco, CA, <https://www.grc.org/>, accessed 14 February, 2026). Table 4 New Article Online
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summarises major classes of blue transformation actions for fisheries resilience and sustainability .

4.4.1. Enhancing efficiency of blue transformation: The efficiency of biotransformation processes, briefly discussed above, can be enhanced for capacity building making use of science-based protocols, namely, zero-waste management, circular economy (CE), use of biorefineries, life cycle analysis (LCA), and digital technologies. The zero-waste strategy allows reduction of carbon footprints, environmental protection, resource intensive growth and economical production. The Zero Waste International Alliance (ZWIA) defined zero waste as ‘the conservation of all resources by means of responsible production, consumption, reuse, and recovery of products and packaging, for materials with no incineration, discharges to land, water, or air that threaten the environment or human health’ (<https://zwia.org/contact-zwia/>, accessed, 2 April, 2024).

Circular economy (CE) strategy aims to minimize waste by creating a closed-loop system that maximizes resource utilization for sustainable production while addressing environmental hazards throughout the supply chain. The CE strategy is in contrast to conventional linear model for waste management, which is characterised by substantial resource inefficiencies, environmental degradation, and socioeconomic challenges. The CE is built upon ‘3R’ model, namely, ‘Reduce-Reuse-Recycle’. Recycling is fundamental characteristic of CE, where the used goods are collected at the end of their life and further used as source material for new products that are safe for humans, animals, and the environment (145). Higher production efficiency and greater utilization of the resources by CE approach fosters sustainable production, besides, reducing environmental pollution and favouring a robust blue economy (146). CE offers a powerful, holistic pathway for small scale fisheries to transition toward greater ecological responsibility and enhanced livelihood



security (21). Many aquaculture farms apply circularity principles in the production processes including recycling of the farm wastes for 'more fish, less waste, blue growth' (147). View Article Online
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Life cycle analysis (LCA) is an environmental tool to quantify the inputs, outputs and global warming potentials throughout the entire life of products, including emissions, resource use, energy and water use. LCA has helped to understand environmental performance of blue foods (28). LCA studies also revealed that valorization of marine waste reduced carbon footprints (136). LCA along with techno-economic analysis (TEA) improves process efficiency and sustainability (148). Application of LCA to the Irish RSW pelagic sector showed that the use of refrigerated seawater trawlers to catch the fish had a low environmental impact and therefore could be an efficient means of food production (149).

Green chemistry can play a fundamental role to promote sustainable development (150). Sustainable techniques in green chemistry often involve substitution of hazardous solvents with novel green solvents for extraction, because of their low toxicity and recyclable nature (151). Upcoming green chemistry-based processing supported by digital technologies has the potential to recover diverse valuable compounds from seafood side streams, while reducing GHG emissions. Other potential advantages include lower energy requirement, lower cost of production, environmentally friendly recovery and retention of functionality of the recovered products (123).

Food waste biorefineries are eco-friendly, and cost-effective platforms functioning on a zero-waste strategy to process biomass including fishery discards. Analogous to the petroleum refinery, the bio-refinery supports sustainable green pathways to produce marketable bio-based products steering resilience of the industry. The biotechnological pathways for biorefinery-based processing fishery discards include fermentation, anaerobic



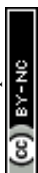
digestion, enzymatic action, along with methods for ingredients extractions. Operation of biorefineries in a cascading manner transforms the waste into valuable products while reducing carbon footprints throughout the chain. A marine bio-refinery envisages conversion of oceanic resources into multiple value-added products, integrating ocean biodiversity into sustainable entrepreneurship offering economic, environmental, and social solutions for a strong blue economy and to safeguard marine ecosystems (152). An effective, scalable circular biorefinery approach to shrimp shell valorization balances product yield, environmental impact, and industrial feasibility in order to contribute to global sustainability goals (153). Pilot plant level studies on a shrimp shell biorefinery showed that the waste can be minimised by recovering proteins, chitin, astaxanthin, and calcium carbonate, which also reduced overall environmental impacts of the shell waste (154). A biorefinery for fish waste recovered protein hydrolyzates, collagen, gelatine, PUFA-rich lipids, and others in a circular process promoting sustainability (155) (156). 'VALORISH' is an EU-funded project to revolutionise valorisation of fish waste and by-products through a sustainable cascade biorefinery approach, transforming the underutilised resources into high-value bioproducts under a computationally-assisted methodology (<https://www.valorish.eu/>, accessed 12 January 2026). Integration of AI, machine learning (ML), and IoT enhances process efficiency enabling the development of smart biorefineries (157). Table 5 summarizes potential eco-friendly processes to bio-transform fishery discards.

4.4.2. High value ingredients from fishery discards and process effluents. The diverse compounds recoverable from capture fishery discards, aquaculture waste and process effluents cover proteins, particularly myofibrillar proteins, collagen and gelatine, bioactive peptides and essential amino acids, PUFA-rich oil, polysaccharides including chitin, chitosan, chondroitin sulphate, glycosaminoglycans, hydrocarbon such as squalene, hydroxyapatite (a naturally occurring mineral), carotenoid pigments, vitamins, among others.



These ingredients, depending upon their natural origin and extraction protocols, display a wide spectrum of bioactivities including antioxidant, anticancer, antithrombotic, anticoagulant, anti-inflammatory, antiproliferative, antidiabetic, antimicrobial, and cardioprotective and other activities. These properties make the ingredients useful in a plethora of application areas such as food additives, dietary supplements, texturizers, natural preservatives, functional foods, medicinal compounds, nutraceuticals, emulsions, films, microcapsules, cell binders, cosmetics, agricultural ingredients, and others. Functional foods and nutraceuticals play a role in the prevention of cardiovascular disease, cancer, metabolic disorders, and neurodegenerative conditions (117). Blue proteins have beneficial impacts on amino acid availability, and are capable to address global protein deficiency (158). Bioactive peptides depending on their structure and spatial configuration, possess anti-hypertensive, anti-diabetic, and anti-oxidant activities, making them valuable medicines besides uses for taste modulation and flavour enhancing functions (159). Collagen is a triple-helical structured protein, widely applied in cosmetics, supplements, films, and biopharmaceuticals. Gelatine, derived by denaturation of collagen under controlled conditions, is a soluble mixture of peptides. The food industry has adopted collagen, collagen peptides and gelatine for various applications that can address food sustainability (160). The PUFA-rich oil from fatty fish such as Atlantic mackerel, anchovies, Atlantic sardine and other oily fish exhibit significant anti-inflammatory, cardiovascular, and hepatoprotective properties such as reduction of blood pressure, lowering cardiovascular disorders and many others (161) (117). Nanotechnology offers enhanced efficiency, sustainability, and food safety across the aquatic value chain. The technology can innovatively enhance functionality of ingredients with possibility for creation of next-generation health solutions. Development of chitosan nanomaterials and other cutting-edge systems promote waste reduction and nutrient recycling. Nano-biosensors enable real-time monitoring, and nano-encapsulated nutrients

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designed for precise delivery with respect to RAS and IMTA farming (162). The diverse areas of applications of chitosan include medical (pharmaceuticals, drug delivery tissue engineering, wound care) food (additives, texturizers), health (nutraceuticals for weight loss, cholesterol lowering, etc), cosmetics (antimicrobials, film formers), agriculture (plant stimulants, antimicrobials, insecticides, etc.), textiles and packaging (biocompatible antimicrobial water repellent coatings), water treatment (flocculants) and other fields (163). The chitin-derived organonitrogen furan, 3-acetamido-5-acetylfuran (3A5AF), is a versatile platform chemical that can be converted into organonitrogen compounds by Diels–Alder reaction. These aspects have been discussed by several authors (97) (163) (164) (165) (166). Integration of marine collagen into chitosan matrices yields sustainable, biocompatible, hemostatic, and genetically safe biomaterials with enhanced regenerative performance, highlighting their strong potential for advanced wound-healing applications (167). The industrial importance of chitosan is indicated by its increasing price. The global chitosan market was valued at \$7.8 billion in 2023 and is estimated to reach about \$43 billion by 2033, exhibiting a Compound Annual Growth Rate (CAGR) of 18.7% from 2024 to 2033 (Allied Market Research, <https://www.alliedmarketresearch.com/>, accessed 2 April 2026). The various wide possibilities, briefly mentioned, have made fishery discards valuable resources attracting considerable commercial interests in them (95) (129) (168).

Consumer acceptability of fishery waste products is an important criterion for their successful food applications. A recent survey showed that consumers are willing to try seafood-incorporated food products including seasoning mix, sauces, and dressing; soup and gravy products (169). Marketing strategies along with legislative protocols can encourage consumer interests in these products (170). Advances in biological science could transform economies and societies, helping to tackle global challenges from climate change to pandemics. Fermented novel proteins could make up about 4 percent of total protein



production by 2050, at a market value of \$100 billion to \$150 billion, the variability being based on climate policies and the pace of technological development (McKinsey, Ingredients for the future: Bringing the biotech revolution to food, April 3, 2025, <https://www.mckinsey.com/> accessed, 9 April, 2025). The market size for marine ingredient is expected to touch US 15 billion by 2030, according to Market Research Report (2024) (<https://www.marketresearch.com>, accessed January 2, 2026).

5.0. Advantages of blue transformation to seafood sustainability

Global demand for blue food is predicted to nearly double by mid-century, particularly with respect to farmed items. The rising demand underscores the international concern about challenges facing aquatic food production and the need for mitigation of these challenges. The nature-positive transformation practices have advantages in supporting seafood sustainability that can meet ecological, economic, environmental and social objectives. Climate-adaptive technologies and practices have significant possibilities to address climate concerns as well as to valorize fishery discards. The scientific approaches minimise food insecurity and hidden hunger, ultimately improving sustainable seafood production and high intrinsic value of marine ecosystems (4) (163) (173) (174). Climate-Improved fishing practices and replacement of fossil fuel with alternate energy sources including bioenergy obtained from transformation of fishery discards, and also solar, and hydrogen can significantly relieve challenges associated with global warming. Novel aquaculture practices have significant role in protecting the environments, while increasing production to meet sustainability targets. There is an urgent need to significantly reduce aquatic food loss and waste, to enhance sustainability and resilience of the global food system. Capacity building is an essential component of blue transformation, ensuring that institutions and stakeholders can develop, utilize and apply science and technology to implement best practices. The benefits of blue transformation of fishery waste biomass are



availability of highly valuable ingredients, along with enhanced resource efficiency, reduced wastage of resources, lower pressure on popular stocks, cutting GHG emissions and environmental pollution. Green processing can be a promising path towards sustainable and economically beneficial utilisation of seafood side streams (123). The resource is available almost throughout the year, its low cost, richness of bioactive compounds, generally low transformation costs and high market values of the recovered products ultimately favour a strong bioeconomy (120) (171) (172). Several valuable novel products can be developed from seafood biomass. For example, fermentation-derived ingredients, particularly alternate proteins, can help feed the world more sustainably (128). Similarly, production of alternate seafood is sustainable, climate resilient, and ethical, and has potentials to achieve global food security and environmental sustainability (143). Chitin, chitosan, and their nano materials and derivatives are highly useful items for sustainable applications in agriculture, textiles, cosmetics, food processing and other industries (120). Fishery lipids have both nutraceutical as well as energy applications. The potentials to utilize all parts of wild caught as well as farmed shrimp including head and shells under '100% shrimp – Full utilization' can provide greater resilience and dampen price volatility, while improving on the carbon footprint and positively contributing to the success of other sectors such as agriculture and pharmaceuticals (97). The '100% Fish Project' in Iceland presents a range of Innovative health-, pharmaceutical- and fashion products made out of cod and other groundfish fish discards making use of up to 90% of the raw material (<https://sjavarklasinn.is/en/home/100-fish/>). The WaSeaBi project, funded by the European Union, transforms low-value side-streams into high-value products contributing to reduce waste and environmental impact (175). Improved utilization of the discarded catch could lead to almost doubling of per capita seafood consumption without increasing the pressure on global fisheries (176).

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Consumer awareness of novel products is important for sustainable fisheries

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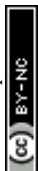
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Consumers also face increasing complexity when making responsible seafood choices.

Collaborative frameworks shared by developers, policymakers, and researchers can create integrated, personalized tools that empower decision-making by consumers for sustainable seafood consumption, health protection and also environmental protection (177). Legislations must be formulated taking into account the appropriateness of particular waste-derived materials for use in food (178) (179) (180). The creation of new markets and product diversification offer promising opportunities to reduce aquatic food loss and optimize resource use. It has been pointed out that if all fisheries were managed sustainably, the edible food from the sea could increase by 21 to 44 Mt by 2050, equivalent to 36 to 74 percent increase, compared to current yields (181). Table 6 points out advantages and weaknesses of valorisation of fishery discards for seafood sustainability.

5.1. Meeting Sustainable Development Goals

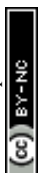
Recognizing the urgency of sustainable development, the United Nations has set the UN 2030 Agenda that has 17 sustainable development goals (SDGs), which aim to achieve sustainability by tackling economic, social and environmental issues that plague the world. These SDGs include poverty elimination (SD 1), zero hunger (SDG 2), good health and wellbeing (SDG 3), clean water and sanitization (SDG 6), affordable and clean energy (SDG 7), sustainable production and consumption (SDG 12), climate action (SDG 13), and life below water (SDG 14). The interconnected nature of the SDGs makes them indivisible, with progress in one area supporting and reinforcing progress in another. The 2025 progress assessment, however, reveals that the world remains far off track from achieving the 2030 Agenda. Although data availability shows encouraging overall progress in meeting SDG goals between 2019 and 2025, persistent gaps in key areas exist, particularly with respect to SDG 13 (182). The Blue Transformation protocols, which align with the Strategic



Framework 2022-2031 of the FAO, have potentials to achieve the objectives of the UN 2030 Agenda (1). Introduction of novel biotechnology-supported production processes enhance environmentally friendly aquaculture that can meet the SDGs, particularly SDG 1 and SDG 2 (183). The bioactive compounds extracted from marine waste exhibit considerable potential in addressing major health issues. This approach aligns with various SDGs viz. SDG 2, 3, 6, 12,13,14 and 15 (136). Table 7 summarises potential contributions of blue transformation protocols to meet the SDGs of the UN 2030 Agenda. In view of these potential benefits, there is need to catalyse change in aquatic food systems through implementation of the Blue Transformation Roadmap (1). The benefits of blue transformation of fishery discards to realize various SDGs are shown in Figure 3.

6.0. Conclusions

This overview briefly discussed major challenges facing sustainable production of blue foods and the potential role of biotransformation protocols to address these challenges . It has been pointed out that concerted transformatory actions involving environmentally friendly protocols can support resilience of aquatic food systems, protecting their ecological, economic and social performance. Integrated science-based and environmentally sound transformation protocols can improve sustainable seafood production controlling overfishing and bycatch, lowering GHG emissions, protecting biodiversity and streamlining aquaculture. These protocols are also able to control of plastic pollution, rejuvenate coral reef, and transform discards into valuable ingredients, which all appreciably contribute to resilience and sustainable seafood supply chain. Science-based farming operations strengthen aquaculture to supplement resources that can meet rising demand for popular farmed fish and shellfish items. The chemical nature of the seafood discards and bycatch being almost comparable to that of high value edible parts, recovery of valuable ingredients and also bioenergy enhance their commercial value, making them contribute to socio-economic



development. Although many of these emerging technologies are under development, there is urgent need for research to streamline protocols for their large-scale applications that can steer seafood sustainability. Success in cohesive, comprehensive and cost-effective blue transformation approaches can realize many SDGs of the United Nations 2030 Agenda. The extent of realizing these SDGs, however, also depend on policy reforms, investments, and public-private partnerships. The marine resources, which are a collective property of nations, should receive international collaborative efforts in conservatory actions. In conclusion, integrated blue transformation solutions can support sustainable fisheries, addressing food security, nutritional deficiencies and social inefficiencies, simultaneously fostering a sound bioeconomy.

Click or tap here to enter text. **Data Availability:**

Openly available data from the following sources have been included in this article:

Academia Edu., Pillai, A.K.B., https://www.academia.edu/s/41b8df7d02#comment_1458671
 Allied Market Research, <https://www.alliedmarketresearch.com/>
 Anthropocene magazine, www.anthropocenemagazine.org
 Arctic council, <https://arctic-council.org>
 Fishery Solution Centre, <https://fisherysolutionscenter.edf.org>
 ICAR-CMFRI, India, <https://www.cmfri.org.in>
 European Commission, 2019. <https://oceans-and-fisheries.ec.europa.eu/fisheries/rules/discarding-fisheries-en>
 FAO, Food and Agriculture Organization of the United Nations, www.fao.org/
 Fishery Solution Center, <https://fisherysolutionscenter.edf.org/>
 Global Seafood Alliance, www.globalseafood.org
 Global Plastic Action, <https://www.globalplasticaction.org>
 Global Salmon Initiative, <http://globalsalmoninitiative.org>
 Good Food Institute
 Gordon Research Conferences, <https://www.grc.org>
 ICAR-Central Marine Fisheries Research Institute, Kochi, India, <https://www.cmfri.org.in>
 International Renewable Energy Agency, Abu Dhabi, <https://coalition.irena.org/>
 International Seafood Sustainability Foundation, www.iss-foundation.org
 Market Research, www.marketreserch.com
 McKinsey & Company, Agriculture, <https://www.mckinsey.com/>
 Ocean acidification program, National Ocean and Atmospheric Organization, <https://oceanacidification.noaa.gov>
 Oceans 2050, <https://www.oceans2050.com>
 Ocean Panel, High Level Panel for A Sustainable Ocean Economy, www.oceanpanel.org



One earth, www.oneearth.org

Seafish, www.seafish.org/

World Bank Group, www.worldbank.org

WorldFish, <https://worldfishcenter.org>

World Meteorological Organization, <https://wmo.int/state-of-global-water-resources-2024>

World Wildlife Fund, www.worldwildlife.org

Zero Waste International Alliance, <https://zwia.org/contact-zwia>

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Declaration

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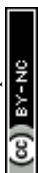
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TABLES

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Table 1. GHG emissions by some wild and farmed seafood

Fishery item	Wild	Farmed
Lobster	19.4	-
Shrimp	12.0	9.4
Bivalves	11.4	1.4
Tilapia	-	10.7
Redfish	9.9	-
Squid	8.2	-
Catfish	-	6.9
Salmon	6.9	5.1
Trout	-	5.4
Cod	5.1	-
Herring	5.4	-

Values are in kg CO₂e per kg of edible meat.

Source: Gephart et al., 2021;

Gaines, J., March 12, 2026, <https://www.anthropocenemagazine.org/>, accessed March 14, 2026.



Table 2. Impacts of major challenges on sustainable seafood production

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Challenge	Impacts
Unsustainable fishing operations	Loss of resources due to overfishing, bycatch, loss of biodiversity, heavy discards from processing operations
Global warming and climate change	Enhanced GHG emissions, sea level changes, heat waves, increased shifts in ocean circulation, ocean currents, melting of glaciers, floods, ocean acidification, diminished oxygen content of water, collapse of coral reef, migration of species, leading to unsustainable and diminished fish and shellfish production
Pollution and toxicity	Organic input due to oil spill, toxic chemicals, radioactive materials, plastics; antibiotics contamination in aquaculture, pesticides, food adulterants; pollution and toxicity from putrefaction of ocean dumped bycatch, process discards; process effluents, etc. Lower production, Unsafe products
Loss of food safety	Microbial contamination of fish and shellfish from pathogens such as <i>Vibrio</i> especially prevalent at high ocean temperatures; Microbial contamination due to intensification of aquaculture practices and other reasons. Unsafe products



Table 3. Key climate adaptive strategies for fisheries

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Strategy	Description
Ecosystem-based management, applying marine spatial planning and integrated coastal and water resource management	Undertake habitat conservation and restoration, adaptive species management, flexible water resources. Consider the entire ecosystem (including the interconnections between species, habitats, and human activities), its health and resilience. Coastal zone management .
Implementation of Marine Protected Areas (MPAs) and multispecies quota systems,	Designed and protected areas considering the movement of species and the impacts of climate change. MPAs may need to be expanded, connected, or adjusted as species shift their ranges or with changes in ecosystems. Quota systems ensure sustainable harvest levels, reduce bycatch.
Climate actions, integrated monitoring and management, increasing adaptive capacity	Climate factors can interact with marine ecosystems for species to adapt to changes and to protect vulnerable species. Use of digital tracking tools and platforms can provide real-time information on the origin, carbon footprint, and sustainability of aquatic foods
Carbon-conscious measures associated with fishing operations, biofuel, renewable energy, use of solar powered agri-food systems, etc.	Reduction of GHG emissions associated with fishing, processing, and transport. Phasing-out of fossil fuel and high emission fishing gear. Utilise renewable energy and low impact gear. Use of biofuels to reduce the dependence on fossil fuels. Examine feasibility of solar, wind, tide energy for fishing. Use satellite data on fishing grounds reduces fishing time and fuel consumption
Science-based management of aquaculture and mariculture	Climate-adaptive practices increase resilience of aquaculture. Use low-input, integrated, and/or non-fed aquaculture systems. Use of low-carbon feeds Energy efficiency standards for aquaculture operations Build healthy fish stocks for resilience. Improve supply chains and market access
Management of fishery discards	Transform fishery discards into valuable resources. Employ green technologies, circularity and LCA principles in supply chains for optimal resource management

Adapted from RENA (2026), NAAS, 2025; Jha et al., 2025; SCOS, 2024; Baiju et al., 2024; Vogel et al. 2024; Galappaththi et al., 2022; Bell et al., 2020.



Table 4. Major blue transformation actions for fisheries resilience and sustainability

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Application area	Description
Capture fisheries	<p>Ecosystem-Based Fisheries Management supported by digital technologies for real-time monitoring of species, animal behaviour, optimization of feeding, water quality, reduction of bycatch, etc.</p> <p>Traceability and certification for reliable production</p> <p>Development of renewable energy for fishing</p> <p>Optimization of trawls and gear types to minimize gear-dependent resistance and operational functionality to reduce emissions.</p> <p>Pollution control through transformative procedures</p> <p>Rejuvenation and restoring of coral reef and mangroves</p>
Sustainable aquaculture	<p>Novel farming technologies such as Recirculating Aquaculture System (RAS), Integrated Multi-Trophic Aquaculture systems(IMTA), aquaponics, mariculture, cage farming, organic aquaculture; precision aquaculture</p> <p>Novel feeds to reduce dependency on fish meal and oil</p> <p>Use of renewable energy</p>
Blue transformation of discards - trash to treasure strategy, supported by zero-waste, biorefinery, circular economy, LCA, and digital technologies	<p>Recovery of highly valuable ingredients, enhancing resource efficiency, reduction of wastage, cutting GHG emissions and environmental pollution, diversify consumption, improves marketability, addresses food insecurity and hidden hunger, improves sustainable seafood production, high intrinsic value of marine ecosystems</p>



Table 5. Some potential eco-friendly processes to bio-transform fishery discards into valuable components

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Ingredients	Methods
Proteins including collagen and gelatin, protein hydrolyzates and bioactive peptides	Fermentation, enzymatic treatment, extractions by green solvents such as ionic liquids (ILs), deep eutectic solvents (DESs), non-thermal technologies, iso-electric solubilization precipitation, membrane filtration, flocculation to recover proteins from process effluents
Lipids	Extractions by enzyme treatment, sub-critical water, subcritical CO ₂ , green solvents, and non-thermal technologies assisted extractions
Carotenoids (astaxanthin, β -carotene)	
Chitin, chitosan, chito-oligosaccharides	Use of microbial fermentation, extractions by green solvents such as ILs, DESs, non-thermal extractions assisted by microwave, ultrasonic, subcritical water, electrochemical and others
Glucosamine, chondroitin sulfate, hyaluronic acid	Fermentation and other eco-friendly processes
Cultivation of single cell proteins (SCP)	
Use of microalgae in integrated biotechnologies facilitates SCP production for rational resource management.	The SCPs can be valuable biomass, particularly rich in proteins, useful for various applications.
Growth of microalgae such as Chlorella in process effluents or nutrient media supplemented with fishery discards	
Cell-cultivated aquatic food products	
Involves harvesting muscle cells from live fish and allowing them to grow in nutrient rich medium under osmolarity conditions comparable to marine habitats.	The process offers a sustainable, climate resilient and ethical approach for nutritive proteins. Reduces usage of wild fish and reduces fishery discards

Sources: Bulynina et al., 2026; Arvelli et al., 2025; Goswami et al., 2024; Venugopal et al 2023.



Table 6. Advantages and weaknesses of valorisation of fishery discards for seafood sustainability View Article Online
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Advantages	Weaknesses
Large scale availability of discards as sources of valuable ingredients and bioenergy almost throughout the year	Sensitivity to rapid spoilage and possible irregular supply of the materials. Likely contamination of pathogenic microorganisms and heavy metals, necessitating consumer safety measures
Potentials to recover ingredients by eco-friendly green processing. Rising demand driven by diverse industries for bioactive and environmentally sound materials	Need for optimization of innovative processes to increase eco-friendly valorization on a commercial scale.
Biotransformation help return of discards into food supply chain, development of industrial fast time-to-market products, diversification of fish consumption, providing socio-economic benefits	Possible high initial investments. Lack of food-grade regulatory approvals for many products. Need for sufficient consumer awareness on the products developed
Minimizes waste, protects the environment and enhances responsible and sustainable seafood consumption	Lack of sufficient information on market potentials of the products. Need legislative actions to expand the range of applicable by-products, focusing on quality and safety standards.
Biotransformation of fishery discards steers blue economy and satisfies various sustainable Development Goals (SDGs)	

Adapted from Minnens et al. 2025; Zou et al.2023; Venugopal, 2022; Peydayesh et al., 2022



Table 7. Potential contributions of blue transformation protocols to the Sustainable Development Goals of the United Nations 2030 Agenda View Article Online
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Contribution field	Sustainable Development Goal (SDG)
Poverty reduction	1.0
Zero hunger	2.0
Good health and well-being	3.0
Clean water and sanitation	6.0
Affordable and cleaner energy	7.0
Decent work and economic growth	8.0
Industry innovation and infrastructure	9.0
Reduced inequalities	10.0
Responsible consumption and production	12.0
Halving seafood resources for sustainable management	12.3
Responsible management of waste	12.4
Substantial reduction of waste generation through prevention, reduction, recycling and reuse	12.5
Sustainable seafood management	12.6
Developing scientific and technological capacity for sustainable consumption	12.9
Alternate fuel for fishing fleet, farming and other seafood related climate actions	13.0
Protection of life below water	14.0
Reduce marine pollution	14.1
Protect marine and coastal ecosystems	14.2
Reduce ocean acidification	14.3
Sustainable fishing	14.4
Conserve coastal and marine areas	14.5
Realize economic benefits	14.7
Increase scientific knowledge, research and technology for ocean health	
Support small scale fisheries	14a
Implement and enforce international law of the sea	14b 14c
Life on land	15.0
Aquaculture	1.0, 2.0, 3.0, 8.0, 10.0, 12.0



Figures

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Figure 1.

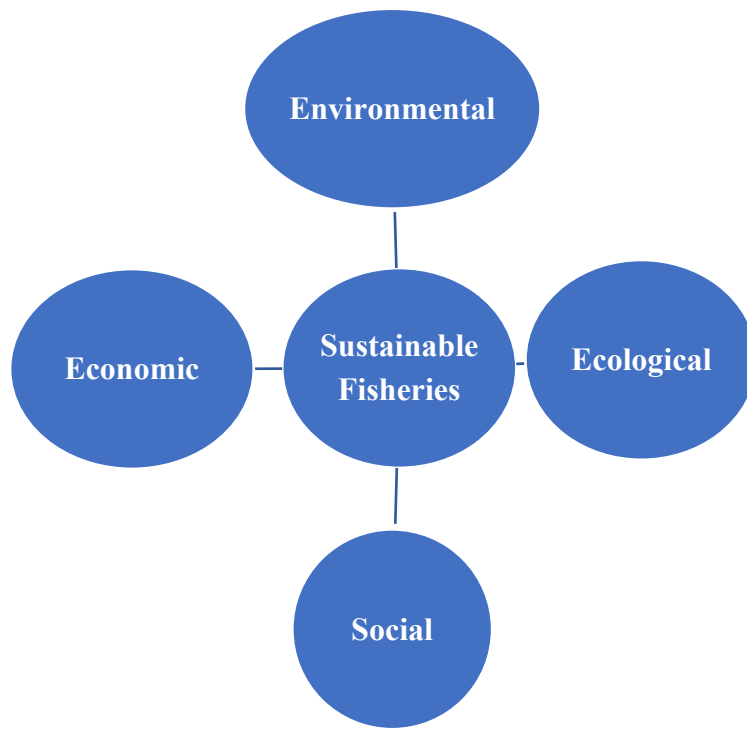


Figure 1. The four pillars for sustainable fishery management

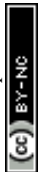


Figure 2

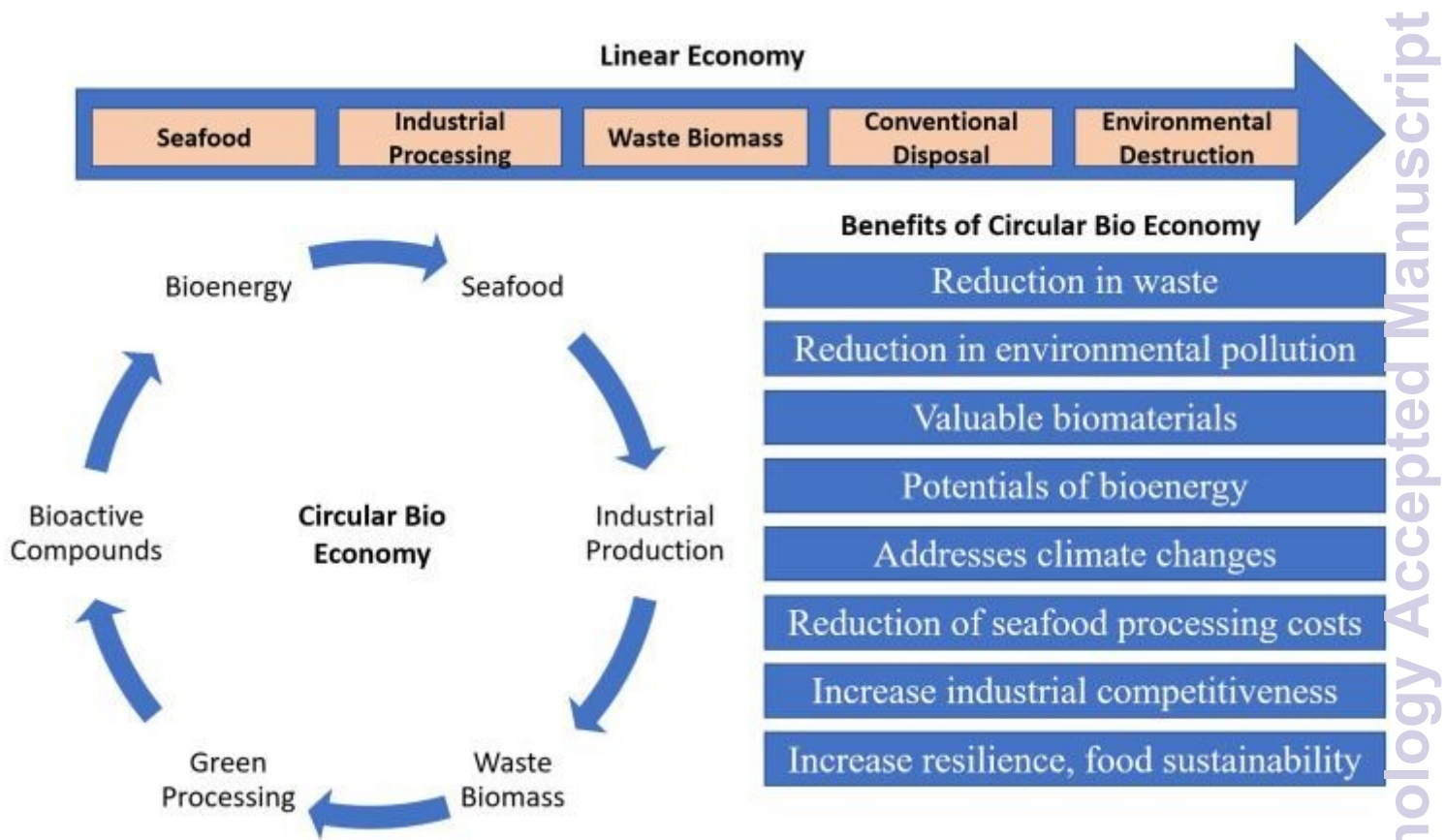
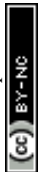
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Figure 2. Seafood waste management: Advantages of circular economy approaches over linear procedures. Reproduced from: 'Green processing of seafood waste biomass towards blue economy', *Current Research in Environmental Sustainability*, Volume 4, 2022; Vazhiyil Venugopal, with permission from Elsevier, www.elsevier.com.



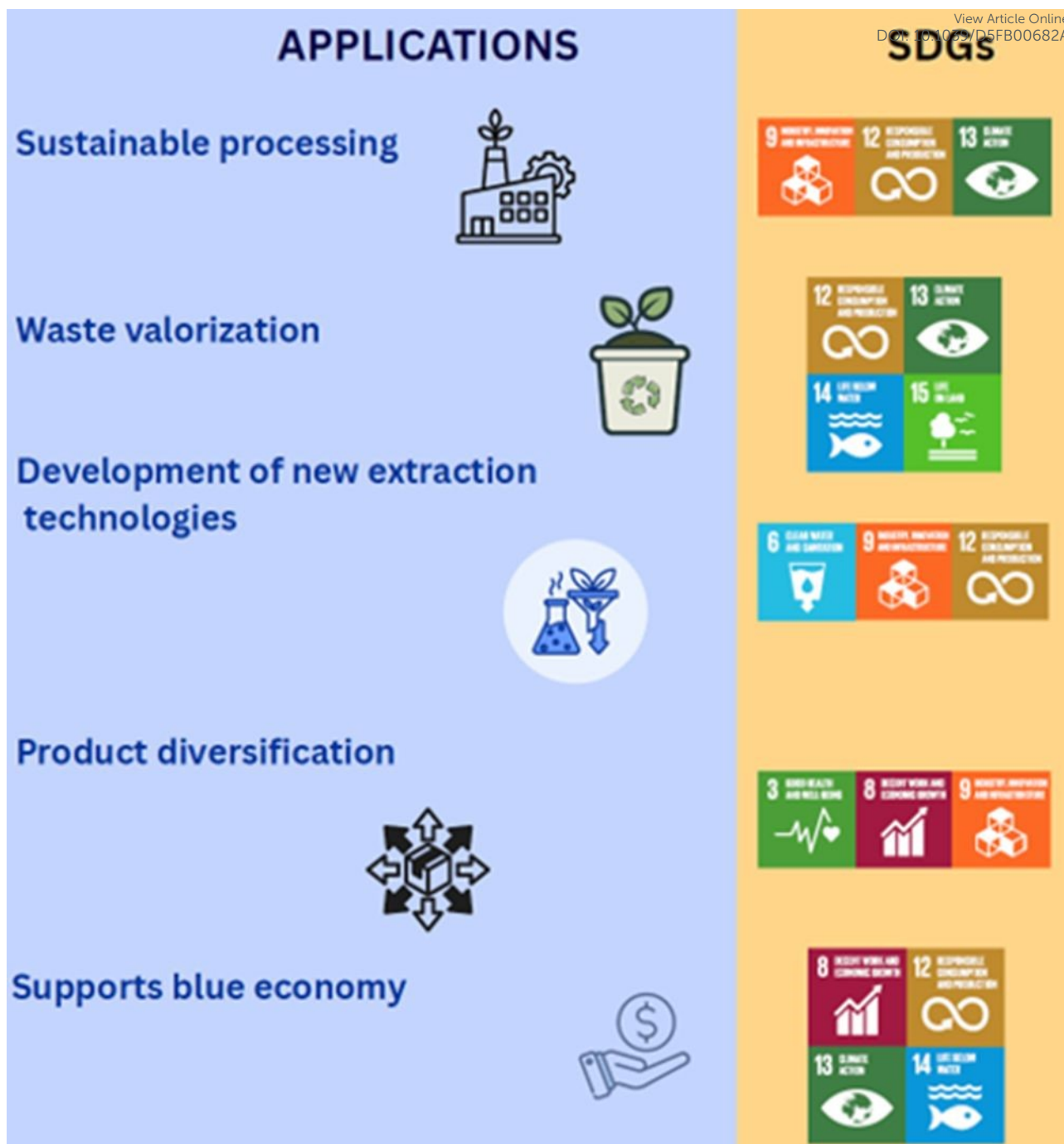


Figure 3. Major potentials of blue transformation of fishery discards to realize SDGs

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Data Availability:

Openly available data from the following sources have been included in this article:

Academia Edu., Pillai, A.K.B., https://www.academia.edu/s/41b8df7d02#comment_1458671
 Allied Market Research, <https://www.alliedmarketresearch.com/>
 Anthropocene magazine, www.anthropocenemagazine.org
 Arctic council, <https://arctic-council.org>
 Fishery Solution Centre, <https://fisherysolutionscenter.edf.org>
 ICAR-CMFRI, India, <https://www.cmfri.org.in>
 European Commission, 2019. <https://oceans-and-fisheries.ec.europa.eu/fisheries/rules/discarding-fisheries-en>
 FAO, Food and Agriculture Organization of the United Nations, www.fao.org/
 Fishery Solution Center, <https://fisherysolutionscenter.edf.org/>
 Global Seafood Alliance, www.globalseafood.org
 Global Plastic Action, <https://www.globalplasticaction.org>
 Global Salmon Initiative, <http://globalsalmoninitiative.org>
 Good Food Institute
 Gordon Research Conferences, <https://www.grc.org>
 ICAR-Central Marine Fisheries Research Institute, Kochi, India, <https://www.cmfri.org.in>
 International Renewable Energy Agency, Abu Dhabi, <https://coalition.irena.org/>
 International Seafood Sustainability Foundation, www.iss-foundation.org
 Market Research, www.marketresearch.com
 McKinsey & Company, Agriculture, <https://www.mckinsey.com/>
 Ocean acidification program, National Ocean and Atmospheric Organization,
<https://oceanacidification.noaa.gov>
 Oceans 2050, <https://www.oceans2050.com>
 Ocean Panel, High Level Panel for A Sustainable Ocean Economy, www.oceanpanel.org
 One earth, www.oneearth.org
 Seafish, www.seafish.org/
 World Bank Group, www.worldbank.org
 WorldFish, <https://worldfishcenter.org>
 World Meteorological Organization, <https://wmo.int/state-of-global-water-resources-2024>
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