Sustainable Food Technology

ROYAL SOCIETY OF CHEMISTRY

REVIEW

Cite this: DOI: 10.1039/d5fb00682a

Blue transformation protocols for resilient and sustainable seafood: an overview

Vazhiyil Venugopal †

The 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, and 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 the control of overfishing, bycatch landing, and climate actions to minimize global warming; (ii) sustainable aquaculture; and (iii) upgradation of the aquatic value chain for social, economic and environmental sustainability. This article, at the onset, briefly discusses the challenges faced by sustainable seafood production followed by the conventional practices to address these challenges. The article then discusses science-based blue transformation protocols that are able to remove weaknesses and encourage the 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.

Received 13th October 2025
Accepted 5th May 2026

DOI: 10.1039/d5fb00682a

rsc.li/susfoodtech

Sustainability spotlight

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 the food security of the rising global population. There is an urgent need to address these challenges faced by sustainable seafood production. Modern strategies for sustainable production rely on science-based blue transformation protocols related to fishing operations, aquaculture as well as the transformation of voluminous fishery discards generated along the supply chain into ingredients as well as bioenergy useful in diverse industries. The article highlights that the science-based transformation of fisheries can meet the sustainable development goals of the United Nations 2030 Agenda.

1 Introduction

The aquatic foods, including fish, shellfish and seaweeds, are also called ‘blue foods’. Blue foods play crucial roles in enhancing food security. Both the wild-caught and farmed fish as well as shellfish are essential components of global food security, providing nutrition, health, and living to their consumers. 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% were used for human consumption. Sixty-two percent of the aquatic animals were harvested from marine waters (69% from wild capture and 31%

Food Technology Division, Bhabha Atomic Research Centre, Mumbai 400 085, India. E-mail: vvenugopalmenon@gmail.com

† Present address: Narayana Mandir, St. Marys College Road, Thrissur, India 680020.

from aquaculture) and 38% from inland waters (84% from aquaculture and 16% from capture). About 730 fishery items worldwide are raised by aquaculture, of which 17 staple species constituted about 60% of the worldwide aquaculture production of 130.9 Mt. Decapod crustaceans, including 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% 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 increased 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. The total consumption of fish and agricultural commodities as well is projected to grow by 13% from the current levels till 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 eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), carotenoids, such as astaxanthin and β-carotene, various vitamins and minerals, making them crucial for global nutritional security.[3] Rising awareness of the nutritional value of fishery products encourages increase in consumption. Aquatic foods can play a 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 fishery production sustainable.[2] Most of the current mitigation efforts in this regard have been traditional in nature such as restricting fishing quota and maintaining protected fishing areas, which have limitations in sustainable production. In view of worsening geo-political and environmental problems as well as rising consumer demands, 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 chain upgradation, including the valorization of fishery discards for sustainable fishery production. The importance of these measures in realizing the sustainable development goals of the United Nations 2030 Agenda has also been pointed out. At the onset, the article briefly discusses various challenges faced by sustainable fisheries, which include illegal and overfishing, landing of voluminous quantities of bycatch, global warming and associated hazards, and pollution.

2 Challenges faced by 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 fishery production systems to 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 the resilience of fisheries and mitigate the 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, mitigates climate change, and creates 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, on average, maintain 40% to 60% of their unfished biomass level. Stocks above 60% of the unfished biomass are considered underfished and those under 40% overfished.[6] Sustainable fisheries are capable of achieving 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, fishery 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 and wellbeing of communities.[7] Fig. 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, the landing of global capture fisheries has more or less plateaued around 100 Mt. The +12% increase in global capture fish production of the current decade is substantially lower than the 24% (37 Mt) increase achieved over the previous decade.[2] The marine conservation society

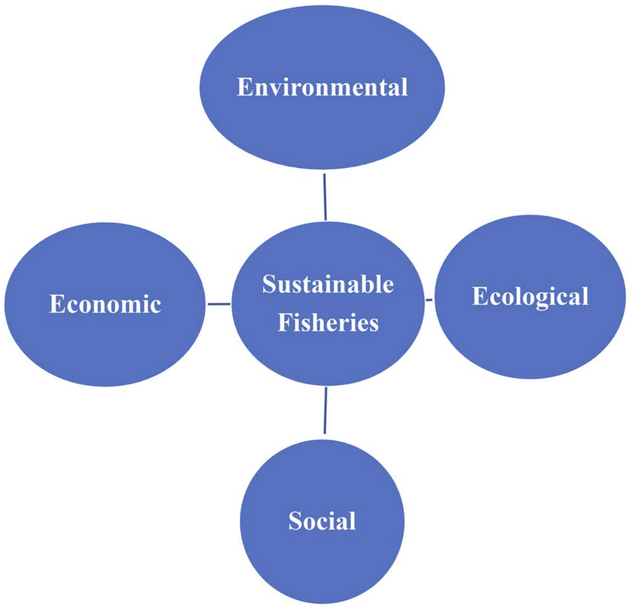

Fig. 1 Four pillars for sustainable fishery management.

(MCS) has downgraded the 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, https://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.

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% in 2021, 2.3% lower than that in 2019.[1,6] Overfishing is a major concern, which affects stocks, undermining the resilience and biodiversity profile of the ecosystems, damaging resource potentials, and ocean economy. Globally, about 37.7% of marine fish stocks are considered overfished, while a further 61% fully exploited and 29% of fishing grounds remained 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 the catch of a total of 60 fish species including 6 crustacean species. Of these, 26% 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 over-exploited 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]

The landing of considerable amounts of low-value fish, which are accidently 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% 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% of total landing.[17] The assessment of bycatch and discards in marine capture fisheries from Navi Mumbai, India, showed the 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 to as artisanal fisheries, play an essential role in ensuring global food security, providing at least 40% (about 37 Mt) of global fishery 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, primarily due to anthropogenic activities, is 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 (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases such as hydrofluorocarbons. The global net GHG emissions were 59 ± 6.6 GtCO_2-eq in 2019, about 10% higher than that in 2010 and 54% higher than that in 1990.[26] Recent increases in global surface temperatures have been tightly coupled with increases in CO_2. 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 that year, the global surface temperature increased by 1.55 °C above the pre-industrial levels, when the globally averaged surface concentrations for CO_2, CH_4 and N_2O reached unprecedented high levels at 424 ppm, 1942 ppb and 338 ppb, respectively. As a result, 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% of annual emissions, compared with the 2019 levels, to reduce the average temperature by 1.5 °C by the year 2035.[23]

The ocean serves as a primary heat reservoir, absorbing about 90% 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 the temperature rising three times the global average, resulting in the accelerated melting of ice and causing sea level rise 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 the 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 the 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% reduction in the depth of fishery biomass-rich photic zone.[25]

Food systems including fisheries contribute 23% to 42% of global GHG emissions. Absolute GHG emissions from food systems increased from 14 to 17 Gt CO_2-eq per year in the period of 1990 to 2018.[26] Cradle-to-grave emissions from food loss and waste represent half of the total GHG emissions from food systems.[27] Global fishing activities are estimated to emit about 180 Mt CO_2e annually, approximately 4% of total GHG emitted by global food systems.[9] Shifting diets towards fish products is capable of reducing 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 GHGs, 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 the highest water use. Across all blue foods, farmed bivalves and seaweeds generate the lowest stressors. The data allow the identification of high-performing blue foods, highlighting the opportunities to improve the environmental performance and develop sustainable diets.[28] Table 1 gives the values of GHG emissions by some wild and farmed seafood items.

Table 1 GHG emissions by some wild and farmed seafoods[a]

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	—

[a] The values are expressed in kg CO_2e per kg of edible meat. Sources: Gephart *et al.*, 2021; and Gaines, J., March 12, 2026, https://www.anthropocenemagazine.org/, accessed March 14, 2026.

2.2.1 Influence on fisheries. Climate change affects primary fishery production in the marine ecosystems, species and stock distributions. Due to climate change, warm-water species are moving into temperate zones, altering the ecosystems.[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. These 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 the collapse of fisheries, 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 has analysed the changes in the biomass of 33 990 fish populations (1566 species) covering major Northern Hemisphere basins during the period of 1993 to 2021. Long-term warming was associated with a decline of fish biomass up to 19.8% per year. On shorter timescales, warmer years and marine heatwaves caused sharp biomass losses of up to 43.4%. 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 the landing of bycatch, stranded and invasive marine species. Changing ocean conditions, driven by temperature increases, have led to shifts in the abundance of lobster, its distribution, larval settlement, disease prevalence, and ultimately changing 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 the 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% 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 them 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 severe and widespread coral damage.[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 the migration of species. Invasive species compete with native species for space, food and other resources, which 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 supports 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, and estuaries), brackish and freshwater (rivers, lakes, reservoirs, *etc.*), and is critical for maintaining habitat-dependent fishery populations. Global 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 an 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 seeds as well as reduced precipitation, leading to increasing competition for freshwater.[41,42] Recently, detailed studies were undertaken to evaluate the temperature effects on the growth of white leg shrimp (grown at 29 °C to 40 °C), giant tiger prawn (35 °C), kuruma prawn (36 °C), the giant freshwater prawn (33 °C to 38 °C); green mud crab (32 °C to 37 °C), lobsters (23 °C to 32 °C), Australian freshwater crayfish (30 °C 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 the feeding behaviour and antimicrobial resistance, increasing the susceptibility to the temperature of farmed crustaceans to disease outbreaks. Ocean acidification and salinity changes negatively influenced the growth, structural formation, tissue formation, reproduction, and shell calcification, reducing the 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 the 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 (NH_3), hydrogen sulphide (H_2S), and others from landfilled, putrefied fishery waste and also effluents from aquaculture causes 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% of global marine plastics. 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%, respectively.[45] The ingestion of MPs can reduce fish growth, leading to reduced biomass. Furthermore, the consumption of MP-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 products (European Commission, 2019, https://oceans-and-fisheries.ec.europa.eu/index_en, accessed on 5 June 2025). These discards, also referred to as side streams or rest raw materials, include heads, viscera, skin, bones, scales, exoskeletons, pens, ink, carapaces, legs, residual meat, and shells. Along highly diverse supply chains, the world lost around 23.8 Mt of edible aquatic food in 2021, representing 14.8% of total production.[26] The amounts of discards, however, depend on the fishery item and process operation. For example, discard volume can be as high as 50% to 70% of whole tuna during canning operation, 40% to 60% of whole shrimp, and about 85% 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 the 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 the impacts of various challenges on sustainable seafood production.

3 Conventional practices for sustainable fisheries in brief

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 of 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 the health of the ecosystem. The code considers the biological characteristics of the resources, their environment and the interests of consumers beneficial 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, https://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

Table 2 Impacts of the major challenges faced by sustainable seafood production

Challenge	Impacts
Unsustainable fishing operations	Loss of resources due to overfishing, bycatch, loss of biodiversity, and voluminous 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, and plastics; antibiotic contamination in aquaculture, pesticides, and food adulterants; pollution and toxicity from putrefaction of ocean dumped bycatch and process discards; process effluents, *etc.*, lower production and unsafe products
Loss of food safety	Microbial contamination of fish and shellfish from pathogens such as *Vibrio* prevalent at high ocean temperatures. Microbial contamination due to the intensification of aquaculture practices and other reasons. Unsafe products

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]

Industrial fishing of threatened fish and invertebrates should be reduced for conservation and sustainability commitments.[11] The 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, and use of acoustic alarms. 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, the 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 developed by ICAR-CIFT, India, is designed for tropical trawlers. It reduces the catch of juvenile fish and non-targeted species by up to 43% while retaining high-value shrimp and large finfish.[55] Cut-away top belly, short belly trawl and high-opening bottom trawls are designs for selective trawling.[55] The selection of gear types is influenced by targeted species, catch potential, resistance offered by gear materials, environmental impact, operational functionality, and 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 Voluntary Guidelines for Sustainable Small-scale Fisheries (SSF) are intended for securing sustainable SSF in the context of food security and poverty eradication.[20] The evaluation of 86 multi-species models helped understanding sustainable production based on population dynamics, growth rate, mortality, biomass, trophic interactions, and other ecological dynamics.[81]

The 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.[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 the impact of aquaculture on mangroves, salt marshes, and seagrasses. The planting of fast-growing mangrove trees can control climate-induced sea level rise, protect fishing zones and minimize vulnerability in coastal regions (https://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 includes 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 Super-highway (AABS) project supports sustainable fishing of the Zanzibar island (https://worldfishcenter.org, accessed February 10, 2026). Catch limits, quotas and related measures have helped rebuild Pacific bluefin tuna fisheries (Waycott, B., Responsible Seafood Alliance, https://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 the management of fisheries. 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 the 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 includes marine ecosystem health, bycatch reduction, and prevention of illegal and overfishing (https://www.iss-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 the 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 the 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 the yield for each fishery on an ongoing basis, which also involves climate-ready fishery management.[80] Table 3 summarises the key climate-adaptive strategies for fisheries and aquaculture.

The conventional practices intended for the sustainability of fisheries 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. Over-exploitation by many fisheries indicates the failure of current approaches to the management of fisheries. 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 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 ensure healthy stocks, (ii) sustainable aquaculture expansion and intensification to meet the 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 mapping resources, implementing nature-based practices, diversifying production, developing value-added products, and market studies, among others. The transformation protocols, which are mostly science-based, turn the supply chain sustainable while meeting legal and ethical standards for the welfare of people, animals, and environment. Cutting-edge technologies on these lines can offer triple benefits, namely, protection of biodiversity, boosting the yield of fisheries 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 the challenges of stock depletion, global warming, environmental changes, and

Table 3 Key climate-adaptive strategies for fisheries[a]

Strategy	Description
Ecosystem-based management, applying marine spatial planning and integrated coastal and water resource management	Undertake habitat conservation and restoration, adaptive species management, and 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 and 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 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, and 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 the feasibility of solar, wind, tide energy for fishing Use of satellite data on fishing grounds reduces fishing time and fuel consumption
Science-based management of aquaculture and mariculture	Climate-adaptive practices increase the 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

[a] Adapted from: RENA (2026), NAAS, 2025; Jha *et al.*, 2025; SCOS, 2024; Baiju *et al.*, 2024; Vogel *et al.* 2024; Galappaththi *et al.*, 2022; and Bell *et al.*, 2020.

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 also 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 and migration of species.[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), and internet of things (IoT) in

Table 4 Major blue transformation actions for the resilience and sustainability of fisheries

Application area	Description
Capture fisheries	Ecosystem-based fisheries management supported by digital technologies for the real-time monitoring of species, animal behaviour, optimization of feeding, water quality, and reduction of bycatch *etc.* Traceability and certification for reliable production Development of renewable energy for fishing Optimization of trawls and gear types to minimize gear-dependent resistance and operational functionality to reduce emissions Pollution control through transformative procedures Rejuvenation and restoring of coral reef and mangroves
Sustainable aquaculture	Novel farming technologies such as recirculating aquaculture systems (RAS), integrated multi-trophic aquaculture systems (IMTAs), aquaponics, mariculture, cage farming, organic aquaculture, and precision aquaculture Novel feeds to reduce the dependency on fish meal and oil Use of renewable energy
Blue transformation of discards: trash to treasure strategy, supported by zero-waste, biorefinery, circular economy, LCA, and digital technologies	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, and high intrinsic value of marine ecosystems

sustainable food production systems. Automation enables the real-time monitoring of animal behaviour, the 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, which 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 (https://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 improve 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). Integrated science-based measures for climate actions including carbon conscious measures, aquaculture development and management of fishery discards are indicated in Table 3.

4.2 Mitigation of the hazards of global warming

Climate action measures are able to transform and reorient fishery systems to support food security, protect marine biodiversity, and ensure sustainability. Delay in addressing climate eventualities seriously affects 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. CO_2 capture, utilization, and sequestration (CCUS) actions for decarbonization include the conversion of CO_2 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 the CCUS technologies are at different stages of development and deployment.[69] Policy options for climate solutions with respect to capture fisheries include the development of sustainable and climate-adaptive management, reduction of emissions from fisheries and support of climate-adaptive practices for fishing communities.[5,26] Ocean-based climate actions can reduce up to one-fifth of the annual GHG emissions (https://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 the cost of production of capture fisheries. The rise in fuel prices due to geopolitical conflicts and other reasons adversely affects fishing activities. Global fishing fleets, powered by diesel, are also responsible for an annual carbon emission up to 159 Mt, contributing to global warming. Green energy transition can significantly mitigate the hazards of global warming and environmental problems. Environmentally friendly alternate fuels are required to reduce cost of fishing operations and to address fishing-related anthropogenic GHG emissions.[16]

Phase-out of fossil fuels along with transition to bioenergy can be a 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. Lipid-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% 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 the 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% for up to 30% reduction in fuel costs and emissions. This could reduce global warming and ocean acidification in the range of 19% to 24%, as determined by life cycle assessment (LCA).[76] An energy-efficient, multipurpose 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 the reduction of fuel use and protection (https://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] Multidisciplinary 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%, 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 the carbon footprint of aquaculture operations. The use of solar photovoltaics (PV) can be practical in agri-food systems including farming operations to reduce the carbon footprints (IRENA, https://coalition.irena.org, accessed March 12, 2026). Renewable energy presents a viable and promising path for sustainable development of aquaculture sector (Centre for Renewable Energy in Aquaculture, https://worldfishcenter.org, accessed, 14 May, 2025). Exploitation of the energy potential of tides, currents, sun light, waves and wind can be interesting future options to reduce emissions associated with fishery 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 related to the 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.[78–80] 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 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 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 plastic treaty can set global standards and 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 CO_2 emission has been suggested. This involves repurposing polyethylene terephthalate plastic waste to capture CO_2 *via* an aminolysis reaction. The reaction products, bis-aminoamide (BAETA) and oligomers, could capture appreciable amounts of CO_2, thereby addressing both plastic waste and CO_2 emissions.[84] An eco-friendly approach to produce hydrogen from fishing net waste (ghost gear) has been reported. The production of H_2 was increased by the pyrolysis of the waste under CO_2. The 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.iss-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 the global goals of food security.[3] As aquaculture expands, strategic planning, investment, and resilience-building measures are essential to reduce emissions as well as the 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] An in-depth understanding of the influence of elevated temperatures on growth performance and physiological responses of aquatic species, including food intake, moulting, immune response, survival, and genetic selection, has significant potential to optimize production and ecosystem-based policies.[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 four 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 farming technologies in recent years. These options are supported by biotechnology, genetics and nutrition, along with innovative management, engineering solutions, and frameworks, which can improve the resilience of aquaculture while minimizing environmental hazards. Recirculating aquaculture systems (RAS) is an intensive approach to fish and shrimp farming, 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 the 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 optimize resource utilization. Pimentel *et al.* (2025) have 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 L^{-1}) 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-to-nitrogen ratio of 15 : 1, while in the Symbiotic, rice bran processed by probiotic microorganisms was used as an organic fertilizer. 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 the 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 makes farming more sustainable and efficient. IMTA reduces environmental impact, enhances resilience, and 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 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 CO_2 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, which make it ideal for species like seabass, groupers, snappers and giant trevally.[55] Mariculture has potentials to decrease carbon footprints up to 40% in comparison with freshwater aquaculture. The 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 the importance of mussels in aquatic ecosystems. Marine mussel farming is sustainable, having potential in enhancing the 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.*, https://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 in waste products of metabolism left behind in their surroundings.[57]

4.3.2 Novel aquafeeds. The current heavy uses of of fishmeal and fish oil for aquafeed production pose sustainability concerns. In 2034, the uses of fishmeal and fish oil are projected to represent 83% of the 21 Mt live weight of fish and other aquatic products.[2] Therefore, novel feeds are essential to reduce GHG emissions, expansion of integrated low inputs, and other practices for the 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 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 have 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 oils 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 the 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] The 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) has 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 the 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 by 15% to 20% and cut labour by 25% to 30%.[109]

The 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 the 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] The 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 the lowest environmental impacts (https://globalsalmoninitiative.org, accessed 18 December, 2025). Ready-to-adopt technology packages for seed, feed, and 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, https://www.worldfishcenter.org, accessed March 20, 2025). It has been forecast that sustainable aquaculture production is expected to grow at least by 35% 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 by the 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, besides, 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.[120–122]

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 systems.[125] Fermentation employs aerobic, anaerobic, facultative or mixed microorganisms including bacteria, fungi, microalgae, or protozoa. The 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, amino acids and other ingredients from food waste.[126] Applications of fermentation processes allow the 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 the 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 the 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 and 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] Integration of innovative manufacturing processes including multi-enzyme cascades, co-culture fermentation, electro-fermentation and others achieve enhanced substrate conversion, product selectivity and overall sustainable production.[132]

Non-thermal extractions employing ultrasonic, microwave, pulse electric field, supercritical fluid and others allow the optimal recovery of ingredients from aquatic sources.[133,134] A green approach for collagen processing involves pre-treatment (fermentation and high-shear mechanical homogenisation) and 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 the extraction efficiency, yield, and purity of ingredients from fishery and other marine wastes. These methodologies enhance nutraceuticals extraction efficiency, yield, and purity, fostering sustainable eco-friendly processes.[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, and enzyme, microwave, ultrasonic, and electrochemical extractions.[137] Steam explosion and supercritical CO_2 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 the recovery of proteins and other ingredients from the effluents of seafood processing industries. The recovery of proteins from these sources reduces carbon footprint, favouring a positive impact on several important planetary boundaries.[47,49,140] The cultivation of microalgae such as *Chlorella vulgaris* and others in seafood process effluents steers the 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% 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 the biotransformation of food waste into novel products. The process for cultivated seafood involves harvesting muscle cells from live fish, immobilizing and allowing them to grow in a 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 the fortification of fish meat with nutrients such as omega-3 fatty acids and others. The 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 summarises the major classes of blue transformation actions for the resilience and sustainability of fisheries.

4.4.1 Enhancing the 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 the 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 the conventional linear model for waste management, which is characterised by substantial resource inefficiencies, environmental degradation, and socioeconomic challenges. The CE is built upon a '3R' model, namely, 'Reduce–Reuse–Recycle'. Recycling is the fundamental characteristic of CE, where the used goods are collected at the end of their life and further used as the 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 the CE approach foster 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 (Fig. 2).[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]

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 the environmental performance of blue foods.[28] LCA studies also revealed that the valorization of marine waste reduced carbon footprints.[136] LCA along with techno-economic analysis (TEA) improves the process efficiency and sustainability.[148] The application of LCA to the Irish 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 the 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 food 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 bio-industry. The biotechnological pathways for biorefinery-based processing fishery discards include fermentation, anaerobic digestion, and enzymatic action, along with the methods for ingredient extraction. The 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 the 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

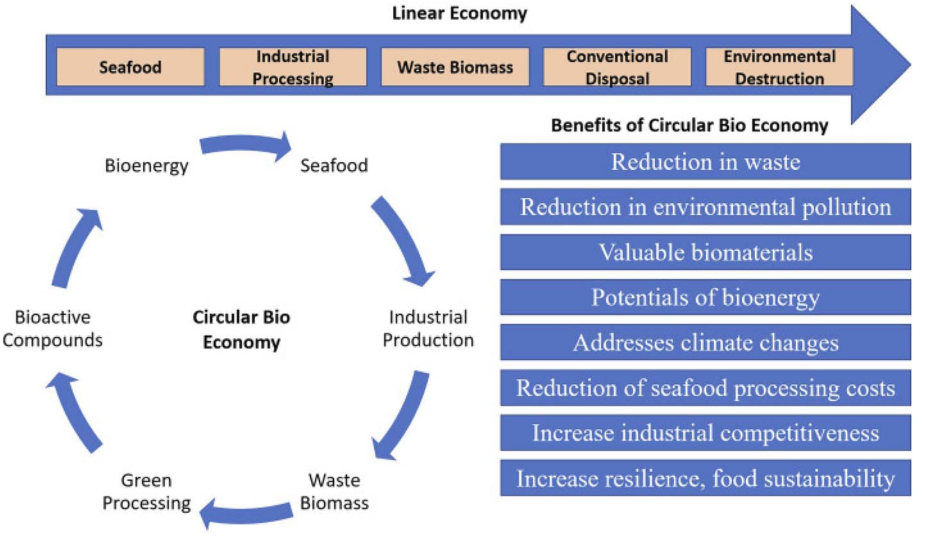

Fig. 2 Seafood waste management: advantages of circular economy approaches over linear procedures. Reproduced from: 'Green processing of seafood waste biomass towards blue economy', Current Research in Environmental Sustainability, Volume 4, 2022; Vazhiyil Venugopal, with permission from Elsevier, https://www.elsevier.com.

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

Ingredients	Methods
Proteins, including collagen and gelatin, protein hydrolysates and bioactive peptides	Fermentation, enzymatic treatment, extractions by green solvents, such as ionic liquids (ILs) and deep eutectic solvents (DESs), non-thermal technologies, iso-electric solubilization precipitation, membrane filtration, and flocculation to recover proteins from process effluents
Lipids Carotenoids (astaxanthin and β-carotene)	Extractions by enzyme treatment, sub-critical water, subcritical CO_2, green solvents, and non-thermal technologies assisted extractions
Chitin, chitosan, and chito-oligosaccharides	Use of microbial fermentation, extractions by green solvents such as ILs and DESs, non-thermal extractions assisted by microwave, ultrasonic, subcritical water, electrochemical and others
Glucosamine, chondroitin sulfate, and 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 Growth of microalgae, such as *Chlorella*, in process effluents or nutrient media supplemented with fishery discards	The SCPs can be valuable biomass, particularly rich in proteins, and useful for aquafeed and other applications
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

[a] Sources: Bulynina *et al.*, 2026; Arvelli *et al.*, 2025; Goswami *et al.*, 2024; and Venugopal *et al.* 2023.

recovering proteins, chitin, astaxanthin, and calcium carbonate, which also reduced the overall environmental impacts of the shell waste.[154] A biorefinery for fish waste recovered protein hydrolysates, collagen, gelatine, PUFA-rich lipids, and others in a circular process promoting sustainability.[155,156] 'VALORISH' is an EU-funded project to revolutionise the 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). The integration of AI, machine learning (ML), and IoT enhances the process efficiency enabling the development of smart biorefineries.[157] Table 5 summarizes the 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, and glycosaminoglycans, hydrocarbons such as squalene, hydroxyapatite (a naturally occurring mineral), carotenoid pigments, and vitamins, among others. These ingredients, depending upon their natural origin and extraction protocols, display a wide spectrum of bioactivities including antioxidant, antimicrobial, anticancer, anti-thrombotic, anticoagulant, anti-inflammatory, anti-proliferative, 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, emulsifiers, natural preservatives, functional foods, medicinal compounds, nutraceuticals, agricultural ingredients, cell binders, and useful to develop emulsions, films, microcapsules, cosmetics, 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 of addressing 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 the 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 others exhibit significant anti-inflammatory, cardiovascular, and hepatoprotective properties such as the reduction of blood pressure and the lowering of cardiovascular disorders.[117,161] Nanotechnology offers enhanced efficiency, sustainability, and food safety across the aquatic value chain. The technology can innovatively enhance the functionality of ingredients with the possibility for the creation of next-generation health solutions. The 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 are 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, and wound care), food (additives and texturizers), health (nutraceuticals for weight loss, cholesterol lowering, *etc.*), cosmetics (antimicrobials and film formers), agriculture (plant stimulants, antimicrobials, insecticides, *etc.*), textiles and packaging (biocompatible antimicrobial water repellent coatings), and water treatment (flocculants).[97,163] The chitin-derived organonitrogen furan 3-acetamido-5-acetylfuran (3A5AF) is a versatile platform chemical that can be converted into organonitrogen compounds *via* the Diels–Alder reaction. These aspects have been discussed by several authors.[97,163–166] The 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 possibilities, briefly mentioned, of converting fishery discards into valuable resources attracted considerable commercial interest.[95,129,168]

Consumer acceptability of fishery waste products is an important criterion for their successful food applications. A recent survey has showed that consumers are willing to try seafood-incorporated edible products including seasoning mix, sauces, dressing, soup and gravy.[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% 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 the Market Research Report (2024) (https://www.marketresearch.com, accessed January 2, 2026).

5 Advantages of blue transformation to seafood sustainability

Global demand for blue food is predicted to nearly double by the 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 the 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 fuels with bioenergy obtained from the transformation of fishery discards can significantly slash challenges associated with global warming. Novel aquaculture practices play a significant role in protecting the environments, while increasing the production that can meet sustainability targets. Valorization of aquatic food waste enhances the sustainability and resilience of the global food system. 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, and 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, the 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 and 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 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 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 wastes and environmental impacts.[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]

Consumer awareness of novel products is important for sustainable fisheries. 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 considering the appropriateness of particular waste-derived materials for use in food.[178–180] 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% increase, compared to the current yields.[181] Table 6 points out the advantages and weaknesses of the 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 (SDG 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

Table 6 Advantages and weaknesses of the valorisation of fishery discards for seafood sustainability[a]

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
Potential 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 helps the return of discards into food supply chain, development of industrial fast time-to-market products, and 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
Biotransformation of fishery discards steers blue economy and satisfies various sustainable development goals (SDGs)	Need legislative actions to expand the range of applicable by-products, focusing on quality and safety standards

[a] Adapted from: Minnens *et al.* 2025; Zou *et al.* 2023; Venugopal, 2022; and Peydayesh *et al.*, 2022.

Table 7 Potential contributions of blue transformation protocols to the Sustainable Development Goals of the United Nations 2030 Agenda

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	14a
Support small scale fisheries	14b
Implement and enforce international law of the sea	14c
Life on land	15.0
Aquaculture	1.0, 2.0, 3.0,8.0, 10.0, and 12.0

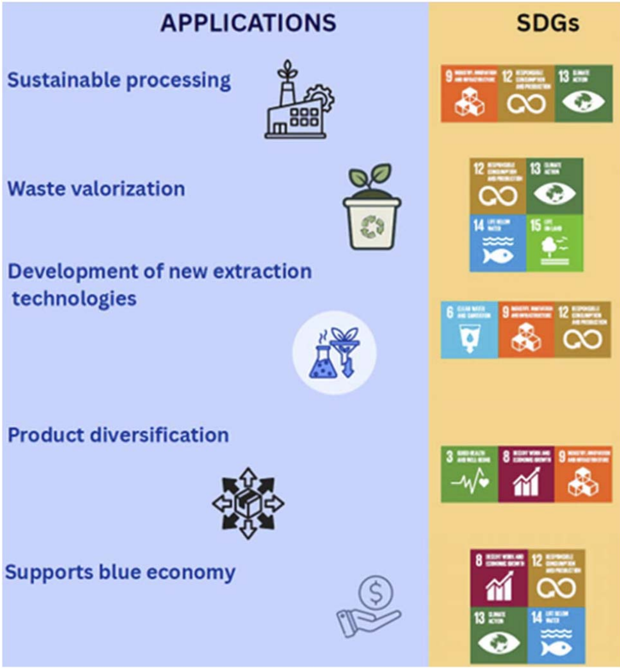

Fig. 3 Major potentials of the blue transformation of fishery discards to realize SDGs.

track from achieving the 2030 Agenda. Although data availability shows encouraging overall progress in meeting the SDGs 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] The introduction of novel biotechnology-supported production processes enhances 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 the potential contributions of blue transformation protocols to meet the SDGs of the UN 2030 Agenda. In view of these likely benefits, there is a need to catalyse the change in aquatic food systems through the implementation of the Blue Transformation Roadmap.[1] The benefits of blue transformation of fishery discards to realize various SDGs are shown in Fig. 3.

6 Conclusions

This overview briefly discussed the 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 methodologies protocols can support the 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 plastic pollution, rejuvenate coral reef, and transform discards into valuable ingredients, which all appreciably contribute to resilience and sustainable seafood production. Science-based farming operations strengthen aquaculture to supplement resources that can meet rising demands for popular farmed fish and shellfish items. With the chemical nature of the seafood discards and bycatch being almost comparable to that of high-value edible parts, the recovery of valuable ingredients and also bioenergy enhance their commercial value, contributing to socio-economic development. Although many of these emerging technologies are under development, there is an urgent need for research to streamline the 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, however, depends 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.

Conflicts of interest

There are no conflicts to declare.

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, Allied Market Research, https://www.alliedmarketresearch.com/, Anthropocene magazine, https://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/index_en, FAO, Food and Agriculture Organization of the United Nations, https://www.fao.org, Global Seafood Alliance, https://www.globalseafood.org, Global Plastic Action, https://www.globalplasticaction.org, Global Salmon Initiative, https://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, https://www.iss-foundation.org, Market Research, https://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, https://www.oceanpanel.org, One earth, https://www.oneearth.org, Seafish, https://www.seafish.org, World Bank Group, https://www.worldbank.org, WorldFish, https://worldfishcenter.org, World Meteorological Organization, https://wmo.int/state-of-global-water-resources-2024, World Wildlife Fund, https://www.worldwildlife.org, Zero Waste International Alliance, https://zwia.org/contact-zwia.

Acknowledgements

Thanks are due to Srikant V. Menon, for handling the reference manager software, and V. Muralidharan, for the critical reading of the manuscript.

References

1 FAO. The State of World Fisheries and Aquaculture, *Blue Transformation in Action*, Food and Agriculture Organization, Rome, 2024.
2 OECD/FAO, *OECD-FAO Agricultural Outlook 2025-2034*, 2025, DOI: 10.1787/601276cd-en.
3 C. D. Golden, J. Z. Koehn and A. Shepon, Aquatic foods to nourish nations, *Nature*, 2021, **598**, 315–320, DOI: 10.1038/s41586-021-03917-1.
4 E. H. Ajandouz, M. Maresca and D. Sarris, Sustainable strategy to fight hidden hunger using food waste: the case of aquatic food products, *Processes*, 2026, **14**, 503, DOI: 10.3390/pr14030503.
5 T. Bahri, M. Vasconcellos and D. J. Welch, *Adaptive Management of Fisheries in Response to Climate Change*, Rome, 2021, DOI: 10.4060/cb3095en.
6 R. Sharma, M. Barange and V. Agostini, *Review of the State of World Marine Fishery Resources – 2025*. Rome, 2025, DOI: 10.4060/cd5538en.
7 C. Roberts, C. Béné and N. Bennett, Rethinking sustainability of marine fisheries for a fast-changing planet, *npj Ocean Sustain.*, 2024, **3**, 41, DOI: 10.1038/s44183-024-00078-2.
8 C. E. Boyd, A. A. McNevin and R. P. Davis, The contribution of fisheries and aquaculture to the global protein supply, *Food Secur.*, 2022, **14**, 805–827.
9 SCOS, *Integrating Blue Foods into National Climate Strategies: Enhancing Nationally Determined Contributions and Strengthening Climate Action*, 2024, DOI: 10.25740/cq607gn4098.
10 E. Witbooi, K. D. Ali and M. A. Santosa, Organized crime in the fisheries sector threatens a sustainable ocean economy, *Nature*, 2020, **588**(7836), 48–56, DOI: 10.1038/s41586-020-2913-5.
11 L. A. Roberson, R. A. Watson and C. J. Klein, Over 90 endangered fish and invertebrates are caught in industrial fisheries, *Nat. Commun.*, 2020, **11**, 4764, DOI: 10.1038/s41467-020-18505-6.
12 WWF, Living Planet Report 2024 – A System in Peril. WWF, Gland, Switzerland. Food loss & waste reduction supporting a circular food economy, *World Wildlife Fund*. 2024, 2024.
13 M. M. Alam, M. S. B. Aziz and M. M. Haque, The extent of destructive fishing gear use in Bangladesh: ecological impacts and strategic roadmap for sustainable fisheries management, *Mar. Policy*, 2025, **181**, 106818.
14 D. Dimarchopoulou, E. Wibisono and S. Saul, Combining catch-based indicators suggests overexploitation and poor status of Indonesia's deep demersal fish stocks, *Fish. Res.*, 2023, **268**, 106854, DOI: 10.1016/j.fishres.2023.106854.
15 C. Möllmann, X. Cormon and S. Funk, Tipping point realized in cod fishery, *Sci. Rep.*, 2021, **11**, 14259.
16 S. Gaines, R. Cabral, C. Free and Y. Golbuu, *The Expected Impacts of Climate Change on the Ocean Economy*, Washington, D C, World Resources Institute, 2019.
17 J. Mendo, T. Mendo and P. Gil-Kodaka, Bycatch and discards in the artisanal shrimp trawl fishery in Northern Peru, *PLoS One*, 2022, DOI: 10.1371/journal.pone.0268128.
18 R. P. Pawar, Assessment of bycatch and discards in marine capture fisheries from Uran (Raigad), Navi Mumbai, Maharashtra, *Ecoscan*, 2011, **5**, 105–109.
19 P. J. Sarlin, P. Joseph and V. A. Bizikov, The First report of the deep-sea oceanic Octopus Amphitretus pelagicus Hoyle, 1885 from the exclusive economic zone of India, *Russ. J. Mar. Biol.*, 2025, **51**, 374–384, DOI: 10.1134/S106307402570052X.
20 X. Basurto, N. L. Gutierrez and N. Franz, Illuminating the multidimensional contributions of small-scale fisheries, *Nature*, 2025, **637**, 875–884, DOI: 10.1038/s41586-024-08448-z.
21 M. M. H. Mozumder and P. Schneider, Advancing sustainability through the circular economy in small-scale fisheries: A global review of practices, challenges, and policy innovations, *Mar. Policy*, 2026, **185**, 107001.
22 WMO, *World Meteorological Organization/Global Atmosphere Watch Greenhouse Gas Bulletin No. 21*, 2025.
23 UNEP, The Emissions gap report 2025, 2025, Available from, https://wedocs.unep.org/handle/20.500.11822/48854.
24 E. J. Fedewa, L. A. Copeman and M. Litzow, Energetic limitations and mass mortality of Bering Sea snow crab: Interacting effects of warming and density on collapse and recovery, *Can. J. Fish. Aquat. Sci.*, 2025, DOI: 10.1139/cjfas-2025-0099.
25 T. W. Davis and T. Smith, Darkening of the global ocean, *Glob. Change Biol.*, 2025, **31**, e70227, DOI: 10.1111/gcb.70227.
26 Intergovernmental Panel on Climate Change (IPCC), *Climate Change: Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 2023.
27 J. Zhu, Z. Luo and T. Sun, Cradle-to-grave emissions from food loss and waste represent half of total greenhouse gas emissions from food systems, *Nat. Food*, 2023, **4**, 247–256, DOI: 10.1038/s43016-023-00710-3.

28 J. A. Gephart, P. J. G. Henrickson and R. W. R. Parker, Environmental performance of blue foods, *Nature*, 2021, **597**, 360–365, DOI: 10.1038/s41586-021-03889-2.
29 A. Bryndum-Buchholz, D. P. Tittensor and J. L. Blanchard, Twenty-first-century climate change impacts on marine animal biomass and ecosystem structure across ocean basins, *Glob. Change Biol.*, 2019, **25**, 459–472, DOI: 10.1111/gcb.14512.
30 E. K. Galappaththi, V. B. Susarla and S. J. T. Loutet, Climate change adaptation in fisheries, *Fish Fish.*, 2022, **23**, 4–21.
31 R. W. Parker, J. L. Blanchard and C. Gardner, Fuel use and greenhouse gas emissions of world fisheries, *Nat. Clim. Change*, 2018, **8**, 333–337.
32 S. Chaikin, J. D. González-Trujillo and M. B. Araújo, Long-term warming reduces fish biomass, but heatwaves shift it, *Nat. Ecol. Evol.*, 2026, **10**(5), 932–941, DOI: 10.1038/s41559-026-03013-5.
33 J. S. Goldstein, B. C. Gutzler and A. S. Kough, A Review of American lobster (Homarus americanus) research since 2000, *Rev. Fish. Sci. Aquacult.*, 2025, 1–56, DOI: 10.1080/23308249.2025.2514440.
34 W. W. L. Cheung, T. L. Frölicher and V. W. Y. Lam, Marine high temperature extremes amplify the impacts of climate change on fish and fisheries, *Sci. Adv.*, 2021, **7**, DOI: 10.1126/sciadv.abh0895.
35 K. Koutsoumanis, A. Allende and A. Alvarez-Ordóñez, Public health aspects of Vibrio spp. related to the consumption of seafood in the EU, *EFSA J.*, 2024, **22**, e8896, DOI: 10.2903/j.efsa.2024.8896.
36 C. M. Eakin, S. F. Heron and S. R. Connolly, Severe and widespread coral reef damage during the 2014-2017 Global Coral Bleaching Event, *Nat. Commun.*, 2026, **17**, 1318, DOI: 10.1038/s41467-025-67506-w.
37 E. Azzurro, *Fisheries Responses to Invasive Species in a Changing Climate*, 2024, DOI: 10.4060/cd1400en.
38 C. Harrold, A. Ramirez and J. Valbo-Jørgensen, How climate change impacts inland fisheries, Barange M., Bahri T., *Impacts of Climate Change on Fisheries and Aquaculture*, FAO Fisheries and Aquaculture Technical Paper No. 627, Rome, 2018.
39 H. M. Christian, The main drivers of biodiversity loss: a brief overview, *Int. J. Nat. Res. Ecol. Manag.*, 2023, **7**, 346, DOI: 10.23880/jenr-16000346.
40 X. E. Elías Ilosvay, N. H. Kumagai, J. García Molinos and E. Ojea, Coastal fisheries adaptations to increasing climate change exposure in Japan, *People Nat.*, 2024, **6**, 2339–2356.
41 P. M. Murshitha, C. P. Ansar and F. P. K. Nishma, The impact of climate change on aquaculture: challenges and adaptation strategies. a review, *Environ. Earth Sci.*, 2025, **11**, 45–61, DOI: 10.35629/2532-11034561.
42 M. Barange, T. Bahri, M. C. M. Beveridge, *et al.*, Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options, *FAO Fisheries and Aquaculture Technical Paper No. 627*, Food and Agriculture Organization, Rome, 2018.
43 V. V. Y. Daunde, M. T. Kamble and B. R. Chavan, Effects of climate change-induced temperature rise on crustacean aquaculture: A comprehensive review, *Acquac. Fish. Manag.*, 2026, **11**, 11–32.
44 V. A. K. B. Gundi, D. Bogireddy and A. K. Vundru, Microbial pathogens in aquaculture: a review of emerging threats, *Proc. Est. Acad. Sci. Biol. Ecol.*, 2025, **3**(3), DOI: 10.20935/AcadBiol7814.
45 E. Arivukumar, R. Shalini and U. Arisekar, Microplastic contamination in thirty commercially important fish species: Distribution, polymer composition, pollution indices, and human health risks, *Mar. Pollut. Bull.*, 2026, **226**, 119360, DOI: 10.1016/j.marpolbul.2026.119360.
46 R. C. Thompson, W. Courtene-Jones and J. Boucher, Twenty years of microplastic pollution research-what have we learned?, *Sciences*, 2024, **386**(6720), 395, DOI: 10.1126/science.adl2746.
47 V. Venugopal and A. Sasidharan, Seafood industry effluents: Environmental hazards, treatment and resource recovery, *J. Environ. Chem. Eng.*, 2021, **9**, 104758, DOI: 10.1016/j.jece.2020.104758.
48 A. Gatto and M. Chepeliev, Global food loss and waste estimates show increasing nutritional and environmental pressures, *Nat. Food*, 2024, **5**, 136–147, DOI: 10.1038/s43016-023-00915-6.
49 M. Peydayesh, M. Bagnani and M. L. Soon, Turning food protein waste into sustainable technologies, *Chem. Rev.*, 2022, **123**, 2112–2154, DOI: 10.1021/acs.chemrev.2c00236.
50 V. Venugopal and S. K. Kim, Mitigation of seafood-related environmental pollution: a green chemistry perspective. *Green and Low-Carbon Economy*, 2025, DOI: 10.47852/bonviewGLCE52023459.
51 FAO, *Code of Conduct for Responsible Fisheries*, Rome, 2005.
52 T. Gray, Fishing for principles: The fairness of fishing quota allocations, *Sustainability*, 2024, **16**, 5064, DOI: 10.3390/su16125064.
53 K. Grorud-Colvert, J. Sullivan-Stack and C. Roberts, The MPA Guide: A framework to achieve global goals for the ocean, *Science*, 2021, **2021**(6560), 373, DOI: 10.1126/science.abf086.
54 M. C. Melnychuk, N. Baker and D. Hively, *Global Trends in Status and Management of Assessed Stocks: Achieving Sustainable Fisheries through Effective Management*, Rome, 2020, DOI: 10.4060/cb1800en.
55 G. John, *Report of Blue Economy Working Group-3 on Fisheries, Aquaculture & Fish Processing Submitted to the Economic Advisory Council*, Government of India, 2019.
56 I. Kwon, G. H. Lee and Y. Seo, Development of a gear-based fisheries management index incorporating operational metrics and ecosystem impact indicators in Korean fisheries, *J. Mar. Sci. Eng.*, 2025, **13**, 1770.
57 P. Kulkarni, A. Kulkarni and S. T. Alware, Sustainability of fished populations challenges, strategies and future directions: a review, *Agric. Sci. Digest*, 2026, DOI: 10.18805/ag.D-6301.

58 E. Gilman, M. Chaloupka and H. Booth, Bycatch-neutral fisheries through a sequential mitigation hierarchy, *Mar. Policy*, 2023, **150**, 105522.
59 V. R. Madhu, A Review of Trawl Selectivity Studies carried out along Indian Coast, *Fish. Technol.*, 2018, **55**(1), DOI: 10.56093/ft.v55i1.79470.
60 Y. Bai, R. Hu and L. Wang, Reduce pollution, establish protected areas, manage fisheries properly? How to protect coral reefs based on carbon trading, *Front. Mar. Sci.*, 2024, **11**, DOI: 10.3389/fmars.2024.1331045.
61 J. Zamborain-Mason, J. E. Cinner and M. A. MacNeil, Potential yield and food provisioning gains from rebuilding the world's coral reef fish stocks, *Proc. Natl. Acad. Sci. U. S. A.*, 2025, **122**(51), e2508805122, DOI: 10.1073/pnas.2508805122.
62 ICRI, *Key Policy Asks for Coral Reefs – Accelerating the Decade of Action #ForCoral*, London, 2025.
63 E. Sala, J. Mayorga and D. Bradley, Protecting the global ocean for biodiversity, food and climate, *Nature*, 2021, **592**, 397–402, DOI: 10.1038/s41586-021-03371-z.
64 A. K. Farmery, K. Alexander and K. Anderson, Food for all: Designing sustainable and secure future seafood systems, *Rev. Fish Biol. Fish.*, 2022, **2**, 101–121, DOI: 10.1007/s11160-021-09663-x.
65 M. S. Rishika, Climate smart aquaculture: Best practices and innovations, *Aquaculture Reimagined: Modern Approaches to Sustainable Fish Farming*, Saini V. P., Biotica Publications, India, 2025. p. 15–22, DOI: 10.54083/978-81-980121-3-5_02.
66 S. V. Bharathi, A. Perdana and T. S. Vivekanand, From ocean to table: examining the potential of Blockchain for responsible sourcing and sustainable seafood supply chains, *Prod. Plann. Control*, 2025, **36**, 950–969, DOI: 10.1080/09537287.2024.2321291.
67 A. Hassoun, A. N. Alhaj and A. Aït-Kaddour, Food traceability 4.0 as part of the fourth industrial revolution: key enabling technologies, *Crit. Rev. Food Sci. Nutr.*, 2022, **64**, 873–889, DOI: 10.1080/10408398.2022.2110033.
68 J. M. Vogel, A. Levine and C. Longo, Fisheries in flux: Bridging science and policy for climate-resilient management of US fisheries under distributional change, *Mar. Policy*, 2024, **170**, 106385, DOI: 10.1016/j.marpol.2024.106385.
69 S. Nagireddi, J. R. Agarwal and D. Vedapuri, Carbon dioxide capture, utilization, and sequestration: current status, challenges, and future prospects for global decarbonization, *ACS Eng. Au*, 2024, **4**, 22–48.
70 E. Razzaq, S. M. Hussain and S. Ali, Transforming fish waste into fuel: A sustainable bioenergy solution, *J. Mater. Cycles Waste Manag.*, 2026, **28**, 799–814, DOI: 10.1007/s10163-025-02457-4.
71 P. Mensah and E. Yankson, Biomass energy as a catalyst for achieving global sustainability goals: technological advancements and policy implications, *Acad. Green Enegy*, 2025, **2**, DOI: 10.20935/AcadEnergy7556.
72 S. S. Karkal, D. R. Rathod and A. S. Jamadar, Fenneropeanus indicus shrimp shell and fishmeal oil: a novel feedstock for biodiesel production and bio derived heterogeneous catalyst development, *Catal. Lett.*, 2024, **154**, 1521–1536, DOI: 10.1007/s10562-023-04396-x.
73 W. O. Sarkodie, F. Takyi, E. Amankwah and M. Takase, A review on the potential of oil from fish waste as a source for biodiesel production in Ghana, *Next Res.*, 2025, **2**(3), 100427, DOI: 10.1016/j.nexres.2025.100427.
74 A. Y. Radeef, A. H. Baher and K. A. Atiya, Improved treatment and bioenergy recovery from fish market wastewater using sediment and plant microbial fuel cells, *Environ. Qual. Manag.*, 2026, **35**, e70277, DOI: 10.1002/tqem.70277.
75 P. N. Jha, M. V. Baiju and L. Edwin, A review of energy use and carbon footprint in fishing with special reference to life cycle assessment (LCA), *Fish. Technol.*, 2025, **62**, 1–15, DOI: 10.56093/ft.v62i1.151686.
76 M. V. Baiju, V. R. Madhu and P. S. Dhiju Das, Evaluating LNG-Diesel dual-fuel system in trawling: Results from trials off Cochin, *Kerala. Fishery Technology.*, 2024, **61**(3), DOI: 10.56093/ft.v61i3.149805.
77 D. Standal and I. A. Ahlquist, Transforming coastal fisheries in Norway: Institutional implications of green technology implementation, *Mar. Policy*, 2025, **171**, 106471.
78 NAAS, *Climate adaptive conservation of fisheries resources*, Indian Counc. Agric. Res. Monogr., 2025, p. 11.
79 B. J. Bell, J. Odell and J. Kirchner, Actions to promote and achieve climate-ready fisheries: summary of current practice, *Mar. Coast. Fish Dynam. Manag. Ecosys. Sci.*, 2020, **12**, 166–190.
80 M. Drexler, E. B. Cerny-Chipman and M. J. P. Williams, Harnessing the value of near-term actions for achieving climate-ready fishery management, *Front. Mar. Sci.*, 2025, **12**, 1558251, DOI: 10.3389/fmars.2025.1558251.
81 P. Couve, N. Bahamonet and C. M. Canales, Systematic review of multi-species models in fisheries: key features and current trends, *Fishes*, 2024, **9**(10), 372.
82 B. Hutniczak, D. T. Wilson and I. J. Stewart, A hundred years of Pacific halibut management in the context of global events and trends in fisheries management, *Front. Mar. Sci.*, 2024, **11**, DOI: 10.3389/fmars.2024.1424002.
83 C. Johnson, A. R. Sierra and J. Dettmer, The bio-based industries joint undertaking as a catalyst for a green transition in Europe under the European Green Deal, *EFB Bioeconomy J.*, 2021, 100014.
84 M. Poderyte, R. Lima and I. M. Golbækdal, Repurposing polyethylene terephthalate plastic waste to capture carbon dioxide, *Sci. Adv.*, 2025, **11**(36), DOI: 10.1126/sciadv.adv5906.
85 H. Lee, J. Im and H. Cho, Hydrogen production from fishing net waste for sustainable clean fuel: Techno-economic analysis and life cycle assessment, *Chem. Eng. J.*, 2024, **481**, 148741, DOI: 10.1016/j.cej.2024.148741.
86 S. Jeyachandran, Review on climate change, microbial resilience, and disease risks in global aquaculture systems, *Comparative Immunology Reports*, 2025, **9**, 200240.
87 R. Zhang, T. Chen, Y. Wang and M. Short, System approaches for sustainable fisheries: A comprehensive

review and future perspectives, *Sustain. Prod. Consum.*, 2023, **41**, 242–252.

88 S. Gupta, P. Makridis and I. Henry, Recent developments in recirculating aquaculture systems: a review, *Aquac. Res.*, 2024, DOI: 10.1155/are/6096671.

89 O. A. L. F. Pimentel, M. H. Schwarz and J. van Senten, The super-intensive culture of Penaeus vannamei in low salinity water: A comparative study among recirculating aquaculture system, biofloc, and synbiotic systems, *Aquaculture*, 2025, **596**, 741774.

90 S. Nissar, Y. Bhaktiyar and M. Y. Araft, The evolution of integrated multi-trophic aquaculture in context of its design and components paving way to valorization via optimization and diversification, *Aquaculture*, 2023, **565**, 739074.

91 T. Xia, Y. Gu and Y. Ma, Nutrient recovery of aquaculture sludge based on phototrophic bioconversion in aquaponics:A Review, *Chem. Eng. Trans.*, 2022, **97**, 193–198, DOI: 10.3303/CET2297033.

92 Y. Liu, Y. Hong and T. Ma, Effects of water flow velocity on growth and nutritional quality of Pacific oysters (Crassostrea gigas), *Fishes*, 2026, **11**(2), 76, DOI: 10.3390/fishes11020076.

93 P. C. Domech, R. Cooney and A. Tahar, Oysters, a sustainable blue food?, *npj Sustainable Agric.*, 2025, **3**, 24, DOI: 10.1038/s44264-025-00065-1.

94 L. Shen, L. Wu and W. Wei, Marine aquaculture can deliver 40 percent lower carbon footprints than freshwater aquaculture based on feed, energy and biogeochemical cycles, *Nat. Food*, 2024, **5**, 615–624, DOI: 10.1038/s43016-024-01004-y.

95 J. Koodathil, K. Elavarasan and H. Munusamy, Mussels: a treasure trove of nutrients, bioactive peptides, and minerals-a review of their applications in food, pharmaceuticals, and biomedicine, *Future J. Pharm. Sci.*, 2025, **11**, 88.

96 R. Naylor, M. Troell and D. C. Little, A 20-year retrospective review of global aquaculture, *Nature*, 2021, **591**, 551–563.

97 M. Siggs, *100% Shrimp - Full utilization: An industry guide*, Global Shrimp Forum Publication, Global Shrimp Forum Foundation, Utrecht, Netherlands, 2026.

98 P. K. Sarkar, B. V. Schoffstall and A. R. Kapuscinski, Towards sustainable aquafeeds: microalgal (Nannochloropsis sp. QH25) co-product biomass can fully replace fishmeal in the feeds for rainbow trout (Oncorhynchus mykiss), *Foods*, 2025, **14**, 781, DOI: 10.3390/foods14050781.

99 M. A. J. Nederlof, S. J. Kaushik and J. W. Schrama, Effect of different types of bacterial single cell protein on feed intake, digestibility, growth and body composition of Pacific white shrimp (Penaeus vannamei), *Aquac. Rep.*, 2023, **33**, 101830.

100 M. H. Wong, W. Y. Mo and W. M. Choi, Recycle food wastes into high quality fish feeds for safe and quality fish production, *Environ. Pollut.*, 2016, **219**, 631–638.

101 S. Rosle, M. S. Mohd Rahim and A. Agustono, Alternative feeds for sustainable aquaculture: a comprehensive structured review, *J. Food Sci. Technol.*, 2024, **10**, 1–11, DOI: 10.11113/jostip.v10n2.150.

102 G. M. Cusimano, C. A. Revue and J. C. Chiang, Management of Atlantic bluefin tuna (Thunnus thynnus) by-products in Malta: Logistics, biomass quality and environmental impact, *J. Clean. Prod.*, 2025, **498**, 145106.

103 S. B. Kurniawan, A. Ahmad and M. F. Imron, Achieving a biocircular economy in the aquaculture sector through waste valorization, *Toxics*, 2025, **13**(2), 131, DOI: 10.3390/toxics13020131.

104 M. R. Soaudy and A. Ghonimy, Microbial activities integration among aquaculture systems for better sustainability – a review, *Ann. Anim. Sci.*, 2026, **26**, 157–172, DOI: 10.2478/aoas-2025-0036.

105 C. M. Aura, H. Awandu, S. Musa and M. J. Ntiba, An approach for the assessment of climate smart technologies for fisheries and aquaculture in an Afrotropical system, *Aquacult., Fish Fish.*, **6**, e70199, DOI: 10.1002/aff2.70199.

106 M. S. Rishika, Climate smart aquaculture: Best practices and innovations, *Aquaculture Reimagined: Modern Approaches to Sustainable Fish Farming*, Saini V. P., Biotica Publications, India, 2025, p. 15–22.

107 K. I. K. Muthmainnah and F. S. Hananto, Internet of things-based water quality monitoring design to improve freshwater lobster farming management, *Int. J. Electr. Comput. Eng.*, 2025, **15**, 3717–3726, DOI: 10.11591/ijece.v15i4.pp3717-3726.

108 M. S. Vidza, M. Budka and W. K. Chai, The applications of complex network analysis in aquaculture and capture fisheries: a systematic review of trends, challenges, and future directions, *Sustain. Futures*, 2025, **10**, 101382.

109 Z. Hashmi, F. Metali and M. Amin, Recirculating aquaculture systems: Advances, impacts, and integrated pathways for sustainable growth, *Bioresour. Technol. Rep.*, 2025, **32**, 102340, DOI: 10.1016/j.biteb.2025.102340.

110 G. Dhanush, A. Sundaramanickam and M. Thangaraj, Metagenomic approach for improved culture of white leg shrimp (Litopenaeus Vannamei), *Proc. Est. Acad. Sci. Biol. Ecol.*, 2025, **3**, DOI: 10.20935/AcadBiol7543.

111 A. D. Diwan, S. N. Harke and A. N. Panche, Studies on exploring the potentials of gut microbiomes to mitigate the bacterial and viral diseases of fish and shellfish in aquaculture farming, *Microbe*, 2024, **2**, 100031, DOI: 10.1016/j.microb.2023.100031.

112 M. M. Khanjani, M. T. Mozanzadeh and E. Gisbert, Probiotics, prebiotics, and synbiotics in shrimp aquaculture: Their effects on growth performance, immune responses, and gut microbiome, *Aquac. Rep.*, 2024, **38**, 102362, DOI: 10.1016/j.aqrep.2024.102362.

113 C. N. Ravishankar, P. S. Ananthan and K. V. Rajendran, Fisheries Sector, *Indian Agriculture by 2047: A Roadmap for Research, Education and Extension*, Pathak H., National Academy of Agricultural Sciences, New Delhi, 2025, p. 121–145.

114 C. Carlino-Costa and M. A. de Andrade Belo, Ensuring Fish Safety Through Sustainable Aquaculture Practices, *Hygiena*, 2025, 5(4), 51, DOI: 10.3390/hygiene5040051.

115 W. C. Valenti, H. P. Barros and P. Moraes-Vaenti, Aquaculture in Brazil: past, present and future, *Aquac. Rep.*, 2021, **19**, 100611, DOI: 10.1016/j.aqrep.2021.100611.

116 L. R. Martínez-Córdova and M. Martínez-Porchas, *Strategies for Sustainable Shrimp Aquaculture*, Elsevier, 2025.

117 V. Venugopal, *Marine Products for Healthcare, Functional and Bioactive Nutraceutical Compounds from the Ocean*. Florida: Taylor & Francis, CRC Press, 2009, 515.

118 B. Rakesh and R. Mahendran, Upcycling of food waste and food loss – A sustainable approach in the food sector, *Trends Food Sci. Technol.*, 2024, **143**, 104274.

119 A. Racioppo, B. Speranza and D. Campaniello, Fish loss/waste and low-value fish challenges: state of art, advances, and perspectives, *Foods*, 2021, **10**, 2725.

120 P. Kashyap, T. Sarkar and S. Maqsood, *Aquatic Waste Valorization, Innovative Approaches and Sustainable Strategies*, Academic Press, New York, 2026.

121 S. A. Siddiqui, H. Schulte and D. Pleissner, Transformation of seafood side-streams and residuals into valuable products, *Foods*, 2023, **12**, 422, DOI: 10.3390/foods12020422.

122 J. L. Vidal, T. Jin and E. Lam, Blue is the new green: Valorization of crustacean waste, *Curr. Res. Green Sustain. Chem.*, 2022, 100330, DOI: 10.1016/j.crgsc.2022.100330.

123 V. Venugopal, A. Sasidharan and T. Rustad, Green chemistry to valorize seafood side streams: An ecofriendly roadmap toward sustainability, *J. Agric. Food Chem.*, 2023, **71**(46), 17494–17509, DOI: 10.1021/acs.jafc.3c03126.

124 V. Venugopal, Valorisation of seafood processing discards: bioconversion and bio-refinery approaches, *Front. Sustain. Food Syst.*, 2021, **5**, 611835.

125 M. Gänzle, J. Seifert and J. Weiss, Food fermentation: an essential unit operation towards secure, sustainable, safe, and sustaining food systems, *Front. Sci. Ser.*, 2025, **3**, DOI: 10.3389/fsci.2025.1693920.

126 M. Ortiz-Sanchez and P. J. Inocencio-García, Potential and restrictions of food-waste valorization through fermentation processes, *Fermentation*, 2023, **9**, 274.

127 S. Tavakoli, Q. Li and W. Han, Valorization of marine crustacean shells waste via fermentation technology: A comprehensive review on derived value-added compounds and enhancing their industrial applications, *Waste Manage.*, 2025, **202**, 114831.

128 M. A. Augustin, C. J. Hartley, G. Maloney and S. Tyndall, Innovation in precision fermentation for food ingredients, *Crit. Rev. Food Sci. Nutr.*, 2023, **93**, 1–21.

129 N. Rossi, C. Grosso and C. Delerue-Matos, Shrimp waste upcycling: unveiling the potential of polysaccharides, proteins, carotenoids, and fatty acids with emphasis on extraction techniques and bioactive properties, *Mar. Drugs*, 2024, **22**, 153, DOI: 10.3390/md22040153.

130 W. Luo, J. Zhang and M. K. Ahmmed, Valorization of animal by-product enzymes: Advancing sustainable food processing through innovative extraction, purification, and application strategies, *Trends Food Sci. Technol.*, 2025, **156**, 104870.

131 A. Annamalai and R. Sasikumar, Enzymatic valorization of fishery by-products: harnessing cold-adapted marine proteases for sustainable production of bioactive peptides, *Arch. Microbiol.*, 2025, **207**, 232, DOI: 10.1007/s00203-025-04431-y.

132 V. Prakash, V. Subasree, P. Arul, *et al.*, Process Engineering Strategies for Enzyme- and Microbial-Based Food Waste Valorization Towards Circular Food Manufacturing, *J. Food Proc. Eng.*, 2026, DOI: 10.1111/jfpe.70525.

133 D. Ağagündüz, K. B. Ayakdaş and F. Ozogul, Advances in non-thermal food processing: a comprehensive approach to nutrient retention, food quality, and safety, *Sustain. Food Technol.*, 2025, **3**, 1284–1308.

134 V. Ayyasamy, H. Ravi and V. Natarajan, Green extraction of marine bioactive compounds and their byproducts using pulsed electric field: mechanisms, applications, and impacts on aquatic foods, *Crit. Rev. Food Sci. Nutr.*, 2025, 1–23, DOI: 10.1080/10408398.2025.2589457.

135 U. H. M. Razali, H. Ya'akob and N. M. Sarbon, Improving collagen processing towards a greener approach: current progress, *J. Chem. Technol. Biotechnol.*, 2023, **98**, 1063–1082, DOI: 10.1002/jctb.7332.

136 N. Khan, R. Vishvakarma and S. Sharma, The blue revolution of marine waste transformation into nutraceuticals: a circular bioeconomy solution for health and sustainability, *Waste Biomass Valor.*, 2025, DOI: 10.1007/s12649-025-03442-6.

137 K. Mohan, A. R. Ganesan and P. R. Ezhilarasi, Green and eco-friendly approaches for the extraction of chitin and chitosan: A review, *Carbohydr. Polym.*, 2022, **287**, 119349.

138 F. Yanhong, L. Hongwei and Y. Xiaochun, An environmentally effective separation strategy of chitin from shrimp shells based on steam explosion and supercritical carbon dioxide, *Ind. Crops Prod.*, 2025, **224**, 120369, DOI: 10.1016/j.indcrop.2024.120369.

139 A. Sasidharan and V. Venugopal, Proteins and Co-products from Seafood Processing Discards: Their Recovery, Functional Properties and Applications, *Waste Biomass Valor.*, 2020, **11**, 5647–5663, DOI: 10.1007/s12649-019-00812-9.

140 S. O. Akpotu, S. M. Nelana and F. M. Mtunzi, Management of wastewater from sea food processing industries: a review, *Strategic Management of Wastewater from Intensive Rural Industries*, Oladoja N. A., Unuabonah E. I., Springer Water, 2025, DOI: 10.1007/978-3-031-90314-4_11.

141 S. S. Bulynina, E. E. Ziganshina and A. D. Terentev, Treatment of wastewater from the fish processing industry and production of valuable algal biomass with a bio-stimulating effect, *Phycology*, 2026, **6**(2), DOI: 10.3390/phycology6010002.

142 A. S. Ray, T. Garg and S. Hazra, Genetic and metabolic engineering for aquatic waste valorization, *Aquatic Waste Valorization, Innovative Approaches and Sustainable Strategies*, Kashyap P., Academic Press, 2026, p. 111–129, DOI: 10.1016/B978-0-443-44027-4.00010-X.

143 N. Nirmal, C. F. Anyimadu and A. C. Khanashyam, Alternative protein sources: addressing global food security and environmental sustainability, *Sustain. Dev.*, 2024, DOI: 10.1002/sd.3338.

144 M. Goswami, R. Ovissipour and C. Bomkamp, Cell-cultivated aquatic food products: emerging production systems for seafood, *J. Biol. Eng.*, 2024, **18**(43), DOI: 10.1186/s13036-024-00436-1.

145 R. Andreazza, C. F. Demarco and J. P. Farias, A sustainable proposal for the fishing chain: Innovative, sustainable, eco-friendly, and social-economic viable, *Environ. Dev.*, 2026, **57**, 101343, DOI: 10.1016/j.envdev.2025.101343.

146 R. Cooney, D. B. de Souza and A. Fernández-Ríos, A circular economy framework for seafood waste valorisation to meet challenges and opportunities for intensive production and sustainability, *J. Clean. Prod.*, 2023, **392**, DOI: 10.1016/j.jclepro.2023.136283.

147 C. Campanati, D. Willer, J. Schubert and D. C. Aldridge, Sustainable intensification of aquaculture through nutrient recycling and circular economies: more fish, less waste, blue growth, *Rev. Fish. Sci. Aquacult.*, 2022, **30**, 143–169, DOI: 10.1080/23308249.2021.1897520.

148 S. Vikram, S. S. Infant and B. S. Balamurugan, Techno-economic and life cycle analysis of biorefineries: assessing sustainability and scalability in the bioeconomy, *Environ. Qual. Manag.*, 2025, **34**, e70077.

149 R. Cooney, A. Kennedy and A. Gallagher, Environmental assessment of Irish seafood: a case study of pelagic fishing, *Sci. Total Environ.*, 2025, **996**, 180161, DOI: 10.1016/j.scitotenv.2025.180161.

150 R. Sánchez Morales, Green chemistry and its role in sustainable development: A systematic review, *Sustainability*, 2024, **16**(15), 6526, DOI: 10.3390/su16156526.

151 K. Venkatesan, J. Sundarababu and S. S. Anandan, The recent developments of green and sustainable chemistry in multidimensional way: current trends and challenges, *Green Chem. Lett. Rev.*, 2024, **17**(1), DOI: 10.1080/17518253.2024.2312848.

152 N. V. Veríssimo, C. U. Mussagy and A. A. Oshiro, From green to blue economy: Marine biorefineries for a sustainable ocean-based economy, *Green Chem.*, 2021, **2021**(23), 9377–9400.

153 J. Naibaho, H. Manikyaparambil and S. Hannon, Trends in shrimp shells valorization for bioactive ingredients extraction: Opinion and perspectives towards circular biorefinery approaches, *Clean. Food Syst.*, 2026, **3**, 100017, DOI: 10.1016/j.clfs.2026.100017.

154 P. A. Aneesh, R. Anandan and L. R. G. Kumar, A step to shell biorefinery—Extraction of astaxanthin-rich oil, protein, chitin, and chitosan from shrimp processing waste, *Biomass Convers. Biorefin.*, 2023, **13**, 205–215.

155 J. M. Gill, S. M. Hussain and S. Ali, Fish waste biorefinery: A novel approach to promote industrial sustainability, *Bioresour. Technol.*, 2025, **419**, 132050, DOI: 10.1016/j.biortech.2025.132050.

156 N. Tkalec, B. Likozar, J. F. B. Pereira and F. A. Vicente, Development of blue-based biorefineries: circular and eco-friendly technologies for processing marine biomass and waste, *Blue Biorefineries and Sustainable Marine Industries*, Vicente F. A., Pereira B., Royal Society of Chemistry, 2025, DOI: 10.1039/9781837678198-00019.

157 S. Arvelli, L. Jia, M. Zhang and J. Zhao, Review of advanced technologies and circular pathways for food waste valorization, *J. Agric. Food Chem.*, 2025, **73**(26), 16085–16108, DOI: 10.1021/acs.jafc.5c03394.

158 S. Fan, Y. Yin, Q. Lio and X. Yong, Blue food proteins: Novel extraction technologies, properties, bioactivities and applications in foods, *Curr. Res. Food Sci.*, 2024, 100878.

159 T. Tufail, H. B. Ul Ain and J. Ashraf, Bioactive compounds in seafood: implications for health and nutrition, *Food Nutr. Sci.*, 2025, **13**(4), e70181, DOI: 10.1002/fsn3.70181.

160 C. T. S. J. Mandal *et al.*, Collagen and Gelatin in Aquatic Waste Valorization, *Innovative Approaches and Sustainable Strategies*, Acad. Press, 2026, DOI: 10.1016/B978-0-443-44027-4.00010-X.

161 R. M. John, A. L. T. Raj and Y. Dinakarkumar, Marine lipids: A review of sources, extraction methods, characterization, and food applications, *Food Human.*, 2025, **5**, 100945.

162 A. R. Sidhu, S. I. Soomro and S. Ahmed, Nanotechnology and closed-loop systems in the aquatic food industry, *Aquatic Waste Valorization, Innovative Approaches and Sustainable Strategies*, Kashyap P., Academic Press, 2026, p. 153–172, DOI: 10.1016/B978-0-443-44027-4.00021-4.

163 S. Advaitha, K. V. Sunooj and M. Navaz, Valorization of side streams to enhance seafood sustainability, *Sustainable Food Technol.*, 2026, DOI: 10.1039/D5FB00236B.

164 S. Taş, N. Y. Döndaş and S. D. Bulut, Recent insight about biotechnological applications of functional seafoods in pharmaceutical industry, *Food Rev. Int.*, 2025, 1–32, DOI: 10.1080/87559129.2025.2526681.

165 S. M. Mawazi, M. Kumar and N. Ahmad, Recent applications of chitosan and its derivatives in antibacterial, anticancer, wound healing, and tissue engineering fields, *Polymers (Basel)*, 2024, **16**, 1351, DOI: 10.3390/polym16101351.

166 T. Wijesekara and B. Xu, New insights into sources, bioavailability, health-promoting effects, and applications of chitin and chitosan, *J. Agric. Food Chem.*, 2024, **72**, 17138–17152, DOI: 10.1021/acs.jafc.4c0216.

167 M. Assis, D. G. N. Nina and K. S. J. Sousa, Green marine collagen–chitosan composites with biocompatible, hemostatic, and pro-healing performance, *ACS Appl. Bio. Mater.*, 2026, **9**(6), 3015–3028, DOI: 10.1021/acsabm.5c02493.

168 S. Naseem, A. Imam and A. S. Rayadurga, Trends in fisheries waste utilization: a valuable resource of nutrients and valorised products for the food industry, *Crit. Rev. Food Sci. Nutr.*, 2024, **64**, 9240–9260, DOI: 10.1080/10408398.2023.2211167.

169 S. Murillo, R. Ardoin and W. Prinyawiwatkul, Factors influencing consumers' willingness-to-try seafood byproducts, *Foods*, 2023, **12**, 1313, DOI: 10.3390/foods12061313.

170 Y. Zou, M. Heyndrickx, J. Debode and K. Raes, Valorisation of crustacean and bivalve processing side streams for industrial fast time-to-market products, A review from the

European Union regulation perspective, *Front. Mar. Sci.*, 2023, **10**, 1068151, DOI: 10.3389/fmars.(2023).1068151.

171 V. Venugopal, Green processing of seafood side streams for a blue economy, *Handbook of Sustainable Blue Economy*, Filho W. L., Springer Nature Switzerland AG, 2025, DOI: 10.1007/978-3-031-32671-4_62-1.

172 V. Venugopal, Green processing of seafood waste biomass towards blue economy, *Curr. Res. Environ. Sustain.*, 2022, **4**, 100164, DOI: 10.1016/j.crsust.2022.100164.

173 M. S. Mia, M. M. Ahmed and W. Zaman, Valorization of food waste into functional ingredients supports a sustainable strategy for the food industry, *Discov. food*, 2025, **5**, 275, DOI: 10.1007/s44187-025-00584-3.

174 M. D. Sahana, A. K. Balange, P. Layana and B. C. Naidu, Harnessing value and sustainability: Fish waste valorization and the production of valuable byproducts, *Adv. Food Nutr. Res.*, 2023, **107**, 175–192, DOI: 10.1016/bs.afnr.2023.08.001.

175 E. Cadena, O. Kocak and J. Dewulf, Valorisation of seafood side-streams through the design of new holistic value chains: WaSeaBi Project, *Sustainability*, 2024, **16**, 1846, DOI: 10.3390/su16051846.

176 R. P. M. Cardinaals, W. J. Simon and F. Ziegler, Nutrient yields from global capture fisheries could be sustainably doubled through improved utilization and management, *Commun. Earth Environ.*, 2023, **4**, 370, DOI: 10.1038/s43247-023-01024-9.

177 F. Minnens, C. Cardoso and C. Afonso, Towards responsible seafood consumption choices: A review of communication tools on health, environmental, and social dimensions, *Trends Food Sci. Technol.*, 2025, **165**, 105292.

178 S. Ahn, D. Jang and C. Oh, Legal issues and improvement strategies for maximizing the utilization of fishery by-products, *Mar. Policy*, 2024, **39**, 97–114.

179 N. B. Rathod, D. Ağagündüz and Y. Ozogul, Incorporation of fish and fishery waste into food formulations: a review with current knowledge, *Trends Food Sci. Technol.*, 2024, **148**, 104517.

180 World Economic Forum, *Investigating Global Aquatic Food Loss and Waste*, 2024.

181 C. Costello, L. Cao and S. Gelcich, The future of food from the sea, *Nature*, 2020, **588**, 95–100, DOI: 10.1038/s41586-020-2616-y.

182 UN DESA, *The Sustainable Development Goals Report 2025*, New York, 2025.

183 K. C. Abeysinghe, W. AGPT and D. K. C. Colonne, Sustainable development goals (SDGs), climate change, and the development of aquaculture and fisheries industries, *Environ. Rev.*, 2025, **33**, 1–24, DOI: 10.1139/er-2024-0136.

