Chapter 5
Use of genetic resources and biotechnology

Key points

- Marine genetic resources hold great potential but remain largely understudied, with most areas beyond national jurisdiction and the deep sea still unexplored. Even marine genetic resources from accessible and well-known marine environments (e.g. coastal areas) are still little investigated compared with genetic resources from terrestrial systems.
- Advancements in the marine genetic resources research and development pipeline have contributed to increasing interest in biodiscovery in marine environments, including the deep sea, particularly of marine microbes, including microbiomes. There are wide-ranging potential applications, including industrial processes, environmental mitigation and health, especially medicines.
- Marine genetic resources, and the fair and equitable sharing of the benefits thereof, are one of four main elements addressed under the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction. Engagement by the scientific community will be necessary to achieve objectives related to marine genetic resources in the Agreement, including advancing conservation and promoting marine scientific research, capacity-building and the transfer of technology.
- Coordination is needed on benefit-sharing relating to marine genetic resources and digital sequence information and the conservation of marine biodiversity within and beyond national jurisdictions across multilateral environmental agreements (the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction and the Convention on Biological Diversity and the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from Their Utilization to the Convention on Biological Diversity).
- Equitable, interdisciplinary approaches to access to and use of marine genetic resources and biotechnology are central to addressing existing knowledge and capacity gaps, and also provide a basis for addressing global challenges of planetary and human health, thereby building sustainable and inclusive futures.

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1. Introduction

A remarkable diversity of life is found in the ocean, which is home to species from 33 of the 34 major animal phyla (Sigwart and others, 2021a). Living organisms have evolved in the ocean for 3 billion years longer than they have on land, with resulting deep evolutionary diversity, and have adapted to thrive in complex habitats, some of which are characterized by extreme temperature, salinity and the absence of light. Extreme conditions and habitat heterogeneity, such as hydrothermal vents and abyssal plains in the deep sea, also drive adaptation and evolutionary novelty (Le Bris and Gaill, 2007; Sun and others, 2020). The vast genomic diversity of marine ecosystems therefore offers a reservoir of genetic resources and biological innovations, with marine organisms producing a wide variety of specific and potent bioactive substances (Carroll and others, 2023; Cordier and others, 2022; Blasiak and others, 2021; Reverter and others, 2020; Arrieta and others, 2010).

In the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, marine genetic resources are defined as "any material of marine plant, animal, microbial or other origin containing functional units of heredity of actual or potential value". Marine genetic resources therefore encompass all forms of marine biodiversity and also provide raw materials for marine natural products, or bioactive chemical compounds produced by marine organisms. Marine biotechnology is the discovery and usage of marine genetic resources (and isolation of marine natural products) for a wide range of potential applications, including human and animal health, improvement of industrial processes, climate change mitigation, bioremediation and the management of invasive species, biomimetics, and areas where marine genetic resources can inspire novel materials and structural design innovations (Blasiak and others, 2020, 2022; Harden-Davies and others, 2020; Jaspars and others, 2016; see also sect. 3).

In recent decades, around 42,000 marine bioactive compounds have been extracted, identified and characterized (Carroll and others, 2023). Marine organisms demonstrate higher bioactivity than terrestrial ones in various studies (Francesch and others, 2024; Saravanan and Debnath, 2013; Appleby and others, 2016). While roughly 1 in 5,000 to 10,000 tested terrestrial compounds leads to applications, this rises to 1 in 2,550 for marine compounds, potentially due to high levels of bioactivity in some species (Royal Society, 2017; Gerwick and Moore, 2012). However, marine and terrestrial compounds appear to be more closely related than previously thought, suggesting that marine genetic resources research should be focused on the subset of unique natural product diversity in the marine realm (Voser and others, 2022). Many new discoveries are expected, including new species (metazoans or microbes), antimicrobial defences, mechanistic pathways, immune strategies and chemical compounds, all with potential applications in biotechnology.

This potential, however, has yet to be translated into a step change in research into marine genetic resources and marine biodiversity (Sigwart and others, 2021a), particularly in the deep sea and areas beyond national jurisdiction, where biodiversity has been little explored. In deep-sea regions of the Pacific, for example, an estimated 80% to 90% of species are new to science (Rabone and others, 2023; Kennedy and others, 2019). Only 0.001% of the deep sea has been visually observed (Bell and others, 2025). To date, marine biodiscovery has been focused on a relatively small group of organisms and habitat types (Francesch and others, 2024). Only 1,639 marine species have genetic sequences associated with patents (Zhivkoplias and others, 2024) of the approximately 250,000 currently known marine species in the World Register of Marine Species database (WoRMS, 2025),[1] with new species discovered at a rate of around 2,300 annually. Only a handful of medicines have been derived from marine genetic resources to date, with the 15 to 20 approved drugs derived from marine sources (Francesch and others, 2024; see also www.marinepharmacology.org/approved) representing a tiny fraction of the discovery potential.

[1] See www.marinespecies.org/.

2. Recent trends and developments since the second *World Ocean Assessment*

Ongoing developments in marine genetic resources research and development and biotechnology have contributed to increasing interest in marine biodiversity (Francesch and others, 2024; Zhivkoplias and others, 2024). The exploration of marine genetic resources has been facilitated in recent years by improved and lower-cost sequencing technologies and bioinformatics tools. Since the publication of the second *World Ocean Assessment*, sequencing techniques have been greatly advanced, including through in situ sequencing platforms, synthetic biology, environmental DNA/metabarcoding, and multiomic approaches utilizing genomic, metagenomic, transcriptomic, proteomic and metabolomic data in tandem (Francesch and others, 2024; Laiolo and others, 2024; Govindarajan and others, 2022; Reverter and others, 2020). Other key developments include the use of artificial intelligence and automation in sampling and collection and analysis (Rabone and others, 2025).

These rapidly developing techniques open up marine environments that have previously been challenging to sample and can facilitate conservation processes, environmental monitoring and biodiversity discovery efforts (Arnaud-Haond and others, 2020; Lewin and others, 2018), as well as establish baselines underpinning global commitments on biodiversity conservation. A total of 1,425 new bioactive compounds were reported from marine organisms in 2021 alone (Carroll and others, 2023). Increased patenting activity of products derived from marine genetic resources is also evident, with 4,779 patent filings referencing marine genes from 1,639 different marine species identified in 2024 (Zhivkoplias and others, 2024). There is an increasing focus on deep-sea species for biodiscovery (Zhivkoplias and others, 2024), likely driven by their high diversity and myriad adaptations to extreme conditions, combined with increasing accessibility. Marine microbes, including host-associated microbiomes of metazoans such as sponges, show great natural product potential (Carroll and others, 2023; Hesketh-Best and others, 2023; Williams, 2009; Bérdy, 2005), and new studies have revealed previously unreported levels of biodiversity and novel function of the global ocean microbiome (Chen and others, 2024; Vohsen and others, 2024; Schubotz and others, 2024). New techniques for rapid microbial biodiscovery are also emerging, including the use of in situ cultivation and metagenomics tools (Bogdanov and others, 2024). Developing applications include bioremediation by genetically modified bacteria (Sajjad and others, 2024).

Pharmaceutical development remains a central focus for research related to marine genetic resources and biotechnology efforts (Francesch and others, 2024; Papon and others, 2022; Lindequist, 2016). More broadly, marine genetic resources remain far less investigated and characterized than terrestrial counterparts (de Jong and others, 2024; Carroll and others, 2023; Voser and others, 2022), and marine biotechnology in some respects can still be considered an emerging or even nascent field (Daniotti and Re, 2021). Large-scale initiatives to map the ocean genome are under way, which are aimed at improving knowledge of marine species and providing libraries of reference genome data to support further research. These include the Earth BioGenome Project (Lewin and others, 2022), the Ocean Genome Atlas Project, the Aquatic Symbiosis Project (McKenna and others, 2024), ATLASea in French exclusive economic zones and the recently developed KAUST Metagenomic Analysis Platform (KMAP) Global Ocean Gene Catalog (Laiolo and others, 2024).

There are also recent developments in governance frameworks for marine genetic resources. The Convention on Biological Diversity and the Nagoya Protocol on Access and Benefit-sharing provide a framework for the fair and equitable sharing of benefits derived from genetic resources from areas within national jurisdiction. Recently, the Conference of the Parties to the Convention on Biological Diversity, in its decision 16/2, adopted modalities for operationalizing a new multilateral mechanism for benefit-sharing from the use of digital sequence information within national jurisdictions. The Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, adopted in 2023 and entering into force in January 2026, provides a new legal framework for equitable access and benefit-sharing of marine genetic resources and associated digital sequence information from areas beyond national jurisdiction (de la Concepción, 2024; see also sect. 3 and subsect. 5B, chap. 5).

3. Pressures and impacts

Our global ocean is under the threat of unprecedented loss of biomass and biodiversity from multiple (and frequently cumulative) anthropogenic pressures, including climate change, pollution and the impact of overfishing and extractive industries (Crona and others, 2021; Vieira and others, 2023). Rapidly changing environmental conditions due to these anthropogenic stressors have resulted in widespread marine ecosystem degradation and biodiversity loss, with impacts evident from coastal habitats to the deep sea and from polar habitats to the equator. In coastal regions, fisheries, aquaculture and coastal development have directly affected habitats, affecting genetic diversity and the populations of certain species, particularly in tropical areas rich in biodiversity such as mangrove forests, coral reefs and seagrass habitats (International Union for Conservation of Nature (IUCN), 2024; Herrera and others, 2022; Morrison and Aalbersberg, 2022; Salimi and others, 2021; Thomas and others, 2017). Climate change has affected the diversity and distribution of marine species through processes of ocean warming, acidification and deoxygenation (Levin, 2018; see also sect. 4, chap. 3). In addition to the manifold negative impacts for humanity from affected ecosystems, countless species and potentially invaluable marine genetic resources (including those that could help to address challenges in planetary and human health) may be lost before they are even discovered. Addressing ocean health is therefore doubly crucial for the conservation of marine biodiversity and marine genetic resources and provides the backdrop for marine biodiscovery and biotechnology activities (see subsect. 5B).

4. Sustainability pathways

Maintaining a balance between the resilience of marine ecosystems and their utilization will require coordination of research, governance and economic activities (including responsible management of global supply chains) (Kittinger and others, 2024). This can be aided by global efforts to address biodiversity knowledge gaps (Laiolo and others, 2024; Rabone and others, 2023; Rogers and others, 2023), the application of genetic/genomic monitoring tools, cooperative interdisciplinary marine scientific/biodiscovery research (Zhivkoplias and others, 2025), holistic approaches to valuing marine genetic resources (Krusberg and others, 2024) and developing sustainability pathways and ocean futures (Pereira and others, 2023). Marine genetic resources and marine biotechnology have often been conceptualized as "future" or "emerging" elements of an ocean economy that generated over $1.9 trillion in revenues in 2019 alone (Claudet and others, 2021; Virdin and others, 2021, World Wildlife Fund (WWF), 2025). It is timely, therefore, to develop pathways for equitable and sustainable use of marine genetic resources (Krusberg and others, 2024). The present part of the chapter introduces aspirational pathways in the lead-up to 2050, envisaging an ideal future in which marine genetic resources are accessed and used in a fair and inclusive manner, contributing a broad range of monetary and non-monetary benefits and improved conservation outcomes (Claudet and others, 2021; Martin and others, 2022). Proceeding along this pathway will require coordinated steps across several disciplines (Crona and others, 2021), as outlined below.

Governance

In our scenario, after the entry into force of the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, a clearing house mechanism and subsidiary bodies will be rapidly established that are tasked with achieving consensus on modalities and levels of benefit-sharing for marine genetic resources. By 2030, the legal clarity provided by the Agreement and its clearing house mechanism will have facilitated a new era of exploration and marine biodiscovery in the deep sea. To ensure fair and equitable access to marine genetic resources, including their utilization for marine conservation, a network of regional centres of excellence will be established, catalysing knowledge exchange. Alongside legally binding regulations, new norms of inclusivity will become increasingly embedded throughout marine scientific endeavours, with each research project (and resulting expedition) composed of scientists from diverse backgrounds (de Vos and others, 2023; Wang and others, 2024; Amon and others, 2022; St Clair, 2021). An extensive library of publicly available novel biotechnologies associated with marine genetic resources will be created alongside benefit-sharing agreements that will have built capacity globally. By 2040, this interconnected network of regional centres might not only

have generated monetary benefits, but also distributed capacity to employ genomic technologies for a wide range of applications in human and planetary health. The utilization of marine genetic resources techniques in setting conservation priorities, monitoring and establishment of networks of marine protected areas (MPAs) will also indicate that the legal frameworks governing marine genetic resources have developed into effective, fit-for-purpose instruments, contributing to improved conservation outcomes.

Economy, markets and technology

As envisioned above, if States have access to marine biotechnology applications and can actively participate in their development, under the guidance of the United Nations Decade of Ocean Science for Sustainable Development (2021–2030), a coordinated international effort will be made to build scientific, technical and computing capacity by 2030 (Blasiak and others, 2020). In this scenario, industry embraces equity and inclusivity as norms of corporate practice, whereby it would publicly announce and share access and benefit-sharing agreements in line with the Nagoya Protocol and the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction. Following the Agreement's entry into force in 2026, the first commercial product from areas beyond national jurisdiction will demonstrate flagship benefit-sharing and knowledge exchange, wherein all phases of research and development, commercialization and sales achieve full compliance with the Agreement and transparency principles and are aligned with scientific best practice. In addition, long-term industry partnerships with the regional centres of excellence could be developed with the aim of advancing the fair and equitable sharing of benefits from marine genetic resources.

As the range of benefits associated with marine biotechnologies becomes widely known, purely economic valuations are expected to increasingly shift to more holistic approaches. These would align with the findings of the values assessment framework of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), which show a broad scope of the values related to nature, including intrinsic (nature for nature), instrumental (nature for society) and relational (nature for culture) values (IPBES, 2022; Krusberg and others, 2024; Islar and others, 2022). As the multiple benefits of marine genetic resources and marine biotechnology become part of public discourse, policymakers might incentivize the use of marine bioresources for biotechnology. In turn, industry could channel resources from successful commercialization efforts into foundations that support scientific research and conservation. By 2050, marine biotechnology could be considered a pillar of the sustainable, equitable and inclusive ocean economy, assessed not only in terms of revenues, but also in terms of its contribution to ocean conservation and sustainable development.

This aspirational pathway is one of many possible scenarios, and includes a number of uncertainties, assumptions and risks, including, for example, risks related to the pace and direction of marine biotechnology progress or the effective implementation of the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction. A business-as-usual pathway would be likely to carry suboptimal outcomes for the environment and for global equity, wherein the current rapid pace of climate change and biodiversity loss would likely continue or even escalate, with attendant but also uncertain socioeconomic and environmental consequences. The description of an aspirational pathway is intended to highlight ideal, sustainable and inclusive futures. The realization of this vision requires global and regional cooperation and the tackling of equity challenges, as outlined in part 5 below.

5. Social components

The advancement of marine biodiscovery is increasingly being recognized as a means to address certain Sustainable Development Goals. There are myriad potential societal benefits from the exploration of and utilization of marine genetic resources, from global health to the development of a sustainable and inclusive ocean economy. Potential benefits include the improvement of global public health (Salicrup and Fedorková, 2006), from addressing the control of zoonoses and the looming antimicrobial resistance crisis to vaccine development and pandemic preparedness (Gamberi and others, 2024; see also subsect. 5B). With antimicrobial resistance, infections become less treatable with current antibiotics, resulting in growing morbidity and mortality (Naghavi and others, 2024; Murray and others, 2022). An estimated 1.14 million people died of an antimicrobial-resistant infection in 2021, and new antibiotics for some of the most significant antimicrobial-resistant pathogens could save

11 million lives between now and 2050 (Naghavi and others, 2024). Most antibiotics currently in use are derived from soil bacteria, but there is significant potential for new antibiotics to be derived from marine environments (Barbosa and others, 2020; Tortorella and others, 2018), especially the deep sea, given the extreme conditions and the increased likelihood that such antibiotics could be derived from undiscovered chemical classes, and therefore act against current antimicrobial-resistant pathogens. This is also true for the most promising alternative to antibiotics, phage therapy (Gordillo and others, 2019), as there are large reservoirs of bacteriophage viruses in marine environments (Breitbart and others, 2018). Alongside deep-sea sediments, another potential source of bacteriophages is the bacteria that form elements of the microbiomes of sponges and other marine animals. The recovery of bacteria from these environments allows for the investigation of their genomes, which can reveal the presence of biosynthetic gene clusters responsible for the production of bioactivity. Some marine-derived bacteria have been shown to be rich in such biosynthetic gene clusters, illustrating their potential as marine natural products (Hesketh-Best and others, 2023).

A sustainable and inclusive ocean economy is one that provides social and economic benefits for current and future generations through its ability to protect, maintain and restore marine biodiversity (Hassanali, 2022). The global blue economy, now known as the sustainable and inclusive ocean economy, has been estimated at $2.5 trillion a year (WWF, 2025). Marine biotechnology offers significant growth potential due to increasing demand for sustainable resources, recent technological advancements, including in molecular techniques, and employment opportunities (Organisation for Economic Co-operation and Development, 2017; Daniotti and Re, 2021). For example, the global marine biotechnology sector creates an estimated 200,000 jobs annually (Rademaekers and others, 2015). Marine biotechnology can therefore support the sustainable development and economic growth of States, including through its potential to address social, economic and environmental challenges (Querellou and others, 2009).

The quantification of the marine biotechnology sector's economic value is challenging, however, due to the lack of a robust economic activity classification system globally for marine biotechnology enterprises. Current estimates of the global market value of marine biotechnology range from 2.5 billion euros and 3.9 billion euros in 2021 (Market Research Future (MRFR), 2024). The medical and pharmaceutical sectors are at the forefront of marine biotechnology, and vaccine development (Gamberi and others, 2024) is expected to contribute substantially to the sector's future growth. These trends reflect the fact that pharmaceuticals and medical applications tend to have high added value (European Commission, 2024). Other high-value applications from marine genetic resources include nutraceuticals, cosmeceuticals and biomaterials, as well as climate and agricultural mitigation applications (Blasiak and others, 2021). Revenues from just five marine-derived drugs (Adcetris, Halaven, Lovaza, Prialt and Yondelis)[2] were found to total over $1 billion per annum (Blasiak and others, 2022; Ottaviani, 2020). Other high-value marine genetic resources include the marine-derived drugs Zovirax and Cytarabine (Ara-C), both derived from the Caribbean sponge, *Tectitethya crypta* (Guilloux, 2018; Lloyd-Evans, 2005) and polymerase enzymes derived from archaea found in hydrothermal vents (e.g. *Pyrococcus furiosus*) and widely used in research and biotechnology (Juniper, 2013).

The benefits of marine genetic resources to society go far beyond monetary valuations (Krusberg and others, 2024). Beyond biotechnology, research on genetics/genomics, such as species diversity and population connectivity, provides insights on ecology and evolution (Jeffery and others, 2022). Because of the unique conditions in which marine genetic resources survive, they can provide essential information about life on Earth and its evolution, as well as improve knowledge of marine biodiversity and the role it plays in the provision of ecosystem services. Such information informs conservation and environmental management. For example, knowledge of species ranges, dispersal potential and population connectivity allows for the design of ecologically cohesive, connected networks of MPAs (Hunter and others, 2024). Non-monetary benefits of equitable marine scientific research (elements of which include the sharing of data, samples and knowledge) can build capacity as well as knowledge with respect to marine biodiversity,

[2] Adcetris is derived from the marine mollusc *Dorbella auricularia* and is used to treat Hodgkin Lymphoma; Halaven is derived from the *Lissodendoryx* marine sponge and is used to treat breast cancer; Lovaza is made from omega-3 fatty acids of fish oils and is used to lower high triglyceride levels; Prialt is derived from the cone snail *Conus magus* and is used to treat chronic pain; and Yondelis is derived from the marine tunicate *Ecteinascidia turbinata* and is used to treat soft tissue sarcoma.

ecosystems and evolution, with improved outcomes for conservation (Harden-Davies and others, 2020, 2024; Rabone and others, 2025; Guilhon and others, 2025).

One primary concern related to utilizing marine genetic resources and biodiscovery activities is the potential impact on marine ecosystems, particularly if products are developed that require a continuous supply of biological materials (Krusberg and others, 2024). To date, however, marine biotechnology has depended on the small-scale collection of samples to discover new molecules that are subsequently synthesized, avoiding further harvesting that may be unsustainable due to low natural abundance or other environmental concerns. Such collection efforts are consistent with general biological sampling principles, for example those employed by taxonomists with the underlying aim of better understanding marine ecosystems, and are subject to the same norms of best practice to minimize ecosystem harm (Hope and others, 2018; Beattie and others, 2011). For example, biodiscovery from microbes can be carried out sustainably if the bacteria can be cultured in the laboratory, avoiding the need to repeatedly sample potentially sensitive environments (Krusberg and others, 2024). By contrast, some products still require the harvesting of wild organisms. For example, high-purity polyunsaturated fatty acids for heart medications are obtained from marine species such as krill (Caffrey and others, 2023). Aside from this medical application, krill and other species are targeted for nutraceuticals by industrial-scale mesopelagic fisheries, giving rise to major concerns regarding sustainability and food web impacts (Fjeld and others, 2023).

Equity

Diverse narratives of a blue economy have emerged, but crucial to most framings is that equity is a guiding motivation for transitioning to an economy that is both sustainable and inclusive (Cisneros-Montemayor and others, 2021; Österblom and others, 2023). In the context of marine genetic resources, the fair and equitable sharing of benefits associated with use is set forth in both the Nagoya Protocol and the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction. Despite regulatory expectations and emerging norms of best practice (Blasiak and others, 2019; Rabone and others, 2019, 2025; Harden-Davies and others, 2024), achieving the aspirational vision of an equitable, sustainable and inclusive ocean economy set out in part 4 of this chapter presents significant challenges. Specifically, imbalances in capacity can lead to fewer opportunities for participation in all stages of the marine biodiscovery process, from accessing the open and deep ocean to conducting laboratory work, research and publication and even participation in scientific conferences (Harden-Davies and others, 2024; Krusberg and others, 2024).

Currently, the ability to conduct research on marine genetic resources is not equal across regions and States (Guilhon and others, 2025; Vierros and others, 2016). Unequal access to marine genetic resources is driven both by disparities in molecular biology and biotechnology expertise and limited access to oceanographic vessels and equipment (Harden-Davies and Snelgrove, 2020; Arnaud-Haond and others, 2011). The expertise to conduct discovery research exists in some centres in the global South, where the richest biodiversity is found with attendant increased likelihood of novel compounds (Harden-Davies and others, 2020). However, investment is required to strengthen capacity and retain trained staff in these global South centres and achieve fair and equitable sharing of benefits arising from this biodiscovery work (Zhivkoplias and others, 2025). To develop the regional centres of excellence in marine genetic resources and marine biotechnology research envisaged in part 4 of the chapter, major capital funding is required for infrastructure development, funding that also needs to be sustained for maintenance and development (Rabone and others, 2019; Collins and others, 2021). These networks could initially be established by developing in-country capacity, for example in sampling and bioinformatics, and progressing through strategic partnerships and joint funding towards the building of repositories and research infrastructure, ultimately leading to interconnected centres. Cooperation and aligned efforts at the regional and international levels (Hassanali, 2022) will prove instrumental.

One recent example of equitable and inclusive marine genetic resource development is a project based in Kiribati, a small island developing State that obtained its first-ever patent (U.S. Patent No. 11,878,057) in a collaboration with researchers based in the United States of America. The discovery of novel deep-sea bacteria was made with minimal environmental impact, requiring no additional sampling beyond normal exploration efforts (Gauthier and others, 2021). Furthermore, the subsequent experiments and inventions do not require any further visit to, or extraction from, the deep sea, as the bacteria can be cultured in the laboratory. These novel bacteria were discovered in filtered water and tissue samples of benthic organisms, then cultured in a laboratory

environment, where they can be maintained in long-term storage. Innovations from these novel, lab-cultured bacteria were patented with named inventors from both Kiribati and the United States (Rotjan and others, 2024). The United States-based institutions covered the full patent fees, but the majority ownership of the patent rests with the Government of Kiribati. While no monetary benefits have yet been realized, the patent itself may be beneficial for conservation outcomes, since this discovery and subsequent invention were motivated by the conservation status of the Phoenix Islands Protected Area. Future conservation efforts in Kiribati and elsewhere will be strengthened by the realization that cutting-edge research can lead to industry pathways that involve equitable partnership. The balance between production and durable ocean protection is essential for enabling pathways for research and development on marine genetic resources that have a low environmental impact and high potential for economic value and conservation efforts (Kittinger and others, 2024). Such projects provide examples that can inform the development of a network of regional marine genetic resource repositories and research centres and the implementation of the provisions of the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction on promoting marine scientific research, capacity-building and technology transfer.

Gender

Considering gender in relation to the use of marine genetic resources and biotechnology is important to achieving equity and the Sustainable Development Goals (Österblom and others, 2023; see also subsect. 5B, chap. 6). However, data on gender are scarce, especially for emergent sectors such as marine biotechnology when compared with traditional sectors of the maritime industry (Ituarte-Lima and others, 2025). Although gender inequality in marine biotechnology has been noted in the literature (Kitada and others, 2015), a lack of available data impedes informed analysis. When examining participation in marine scientific research, persistent gender bias patterns have been reported for European Union marine sciences and conservation (Giakoumi and others, 2021; Lima and Rheuban, 2022). The situation is more acute for women in the global South, but, again, data are lacking (Shellock and others, 2022). Fundamental issues of women's safety at sea while conducting scientific research (including within industrial contexts such as fisheries or oil and gas exploration) have also been raised in the literature, which shows that multiple factors contribute to a challenging work environment (Amon and others, 2022; Johannesen and others, 2022, 2025; Maia and others, 2024). Implementing frameworks to address fundamental equality issues including work environments at sea, particularly for women of the global South, is needed to advance gender equity (Amon and others, 2022; Johannesen, 2025).

More broadly, recommendations are being put forward at the United Nations and OECD to address gender equality in marine scientific research and to acknowledge the contributions of women and girls in marine conservation efforts (IOC-UNESCO, 2024). There have been calls to mainstream gender equality in legislation and policy frameworks to promote the creation of better employment opportunities for women across the blue economy (United Nations Entity for Gender Equality and the Empowerment of Women (UN-Women), 2020; Rahaman and others, 2024). However, these policies are not yet widespread in ocean-related activities, including those directly linked to marine genetic resources, such as marine biotechnology, where data remain scarce. Examples of women's participation in the blue economy in developing countries include women-led small-scale local fisheries and aquaculture in sub-Saharan Africa and the Indian Ocean Rim, with outcomes both positive and more equivocal, which underscore the need to support women's active participation (UN-Women, 2020; FAO, 2020). Enhancing women's roles in sustainable and innovative uses of marine genetic resources would contribute to a more equitable blue economy, alongside efforts to address the root causes of gender inequalities, collaborate with men and boys to challenge stereotypes and create conducive environments for women-led initiatives in the ocean space (IOC-UNESCO, 2024).

Traditional knowledge

The traditional knowledge of Indigenous Peoples and local communities associated with the management of marine resources, the understanding of species behaviour and medicinal applications dates to ancient times, with references in Indian, Chinese, Greek and Arabic texts (Voultsiadou and Vafiis 2007; Gopal and others, 2008). The Pacific region in particular has a rich tradition of traditional knowledge and cosmologies that directly relate to marine genetic resources (Hau'Ofa, 2008; Mulalap and others, 2020). Traditional knowledge has long been and continues to be vital to the conservation and sustainable use of the ocean and marine genetic resources (Mulalap and others, 2020). There is a growing focus on integrating traditional knowledge into ocean governance

and management (Pena-Neira and Coelho, 2025). Studies have shown that marine species used in traditional medicine belong to groups rich in bioactive natural products, namely sponges, cnidarians, molluscs, echinoderms and tunicates, pointing to the potential of traditional knowledge on marine species for the discovery of novel bioactive compounds (Herbert and others, 2003). A recent example of traditional knowledge and marine genetic resources is the oyster *Crassostrea (Magallana) saidii*, a species first identified by traditional knowledge and maintained as a separately managed fishery for over 120 years before it was formally described (Sigwart and others, 2021b). The local fishers could distinguish the "new" species from a co-occurring congener consistently, but scientists could not; the fishers' identifications were 100% accurate, as confirmed by DNA barcoding and morphometrics (Sigwart and others, 2021b).

However, links between scientific discovery associated with marine genetic resources and traditional knowledge are rare, in large part due to a disconnect between scientists undertaking biodiscovery research and the Indigenous Peoples and local communities who hold the knowledge. Furthermore, there is a great disparity between the holders of traditional knowledge and scientists in the global North in terms of capacity to explore and utilize marine genetic resources (Armitage and others, 2020). In addition, Western science and traditional knowledge follow different epistemologies in terms of knowledge production. While the former relies on rigorous methodological approaches and generalizations, the latter is localized and tied to the experiences, observations and practices passed down through generations, which are often tied to cultural, ecological, medicinal, social, agricultural and spiritual practices (Hockings and others, 2019). For medicinal examples, differences between traditional knowledge and scientific knowledge in relation to marine genetic resources arise because traditional knowledge systems encompass not only medicinal uses but also the social-spiritual dimensions of traditional medicine that cannot be readily translated into scientifically evaluated and medically approved patent medicines (Williams and Whiting, 2016). This disconnect raises ethical and legal challenges with respect to benefit-sharing, as researchers may lack awareness of associated traditional knowledge and communities may face challenges in accessing information, organizing and navigating access and benefit-sharing negotiations. Furthermore, inadequate legal frameworks exist for recognizing the knowledge systems of Indigenous Peoples and local communities and protecting the intellectual property rights of traditional knowledge holders. This is magnified by the fact that traditional knowledge systems and cosmologies are often held in oral rather than written records and across communities and geographical boundaries, especially in the case of marine species. Moreover, traditional knowledge is not bound by the legal fiction of jurisdictions under international law (Menime and others, 2022). The governance of traditional knowledge falls under the Convention on Biological Diversity for marine genetic resources from areas within national jurisdiction and the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction for the marine genetic resources of areas beyond national jurisdiction. Benefit-sharing under the Convention on Biological Diversity may involve bilateral agreements between the Indigenous Peoples and local communities of provider States and resource recipients. This approach facilitates direct benefit flows to traditional knowledge holders. To harmonize legal frameworks governing marine genetic resources and to support the fair and equitable sharing of benefits, facilitating the connection between traditional knowledge and scientific research could foster more inclusive biodiscovery and innovation (Rabone and others, 2025; Pena-Neira and Coelho, 2025).

6. Governance

Key legal frameworks governing the fair and equitable benefit-sharing of marine genetic resources and digital sequence information include the Nagoya Protocol under the Convention on Biological Diversity and the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction, for areas within and beyond national jurisdiction respectively. Over the past decade, challenges linked to the effective implementation of the Nagoya Protocol have been identified (Laird and others, 2020; Prathapan and others, 2018). While these instruments have been ratified by many States, capacity constraints mean that many of these States have not yet implemented relevant administrative procedures (Ivey and others, 2023). The bilateral structure of the Nagoya Protocol necessitates navigation of the legislation on a country-by-country basis, which can be burdensome for users (Laird and others, 2020; Emery and others, 2025). Work is ongoing under the auspices of the Convention on Biological

Diversity to address some of these challenges. In relation to digital sequence information, there has been a shift towards a more harmonized approach to benefit-sharing with adoption of the multilateral mechanism on digital sequence information and the creation of the Cali Fund for the Fair and Equitable Sharing of Benefits from the Use of Digital Sequence Information on Genetic Resources (Conference of the Parties to the Convention on Biological Diversity decision 16/2), a global benefit-sharing mechanism (Convention on Biological Diversity, 2024; Sett and others, 2024; Scholz and others, 2022). There is a need for coordination across the Convention and its Nagoya Protocol (including on digital sequence information multilateral benefit-sharing) and the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction. More broadly, harmonization across agreements can support global commitments on conservation and the sustainable use of biodiversity and align with benefit-sharing targets under the Kunming-Montreal Global Biodiversity Framework, adopted at the fifteenth Conference of the Parties to the Convention on Biological Diversity in December 2022. At the time of writing, with rapid recent ratifications by States, the Agreement has already reached the threshold for entry into force, surpassing expectations (Blasiak and Jouffray, 2024). However, national and institutional capacity varies widely across States and regions, with some at risk of being left behind (Ardron and others, 2025; Rabone and others, 2025; Gjerde and others, 2022). For current and future generations to benefit equitably from marine genetic resources in areas beyond national jurisdiction, as anticipated under the Agreement, legislative and institutional preparations will need to begin now.

Adopted in June 2023 and entering into force in January 2026, the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction addresses a package of objectives geared towards achieving the conservation and sustainable use of biodiversity beyond national jurisdiction. The objectives relevant to marine genetic resources include fair and equitable benefit-sharing, capacity-building, knowledge generation and marine technology transfer (art. 9). The Agreement applies to activities relating to the collection and use of marine genetic resources and digital sequence information sourced from areas beyond national jurisdiction after the entry into force of the Agreement, excluding fishing regulated under international law and fish or other living marine resources known to have been taken in fishing and fishing-related activities from areas beyond national jurisdiction (art. 10). The Agreement applies to the utilization of marine genetic resources and digital sequence information collected or generated before its entry into force unless a Party expresses an exception in writing (art. 10 (1)). Such activities can be carried out in areas beyond national jurisdiction by all Parties, regardless of their geographical location, and by natural and juridical persons under their jurisdiction (art. 11 (1)). Relevant activities must be carried out with due regard for the rights and legitimate interests of coastal States in areas within national jurisdiction, as well as those of other States active in areas beyond national jurisdiction (art. 11 (3)). The interests of all States must be taken into account, particularly the interests and needs of developing States (art. 11 (6)).

Specific notification requirements have been created with respect to the collection and utilization of these resources. Parties are required to take the necessary legislative, administrative or policy measures to ensure that information is provided to the clearinghouse mechanism at various stages of the process. Article 12 (2) (a)–(j) lists the information that must be provided six months prior or as early as possible before the in situ collection occurs, after which time a standardized batch identifier shall be generated (art. 12 (3)). This is a persistent (or permanent) unique identifier that follows marine genetic resources and digital sequence information through the research and commercialization journey. Although this is a grouping identifier associated with a whole research cruise or equivalent "batch", its utility rests on the fact that it can be used to identify research, development and commercialization activities involving marine genetic resources and digital sequence information, making this a "light touch" end-user traceability mechanism (Lawson and others, 2025; Rabone and others, 2025; Thambisetty and others, 2023, 2025). After in situ collection has taken place, Parties are required to ensure that information regarding, inter alia, where collected marine genetic resources and digital sequence information will be deposited, the geographical location from which marine genetic resources were collected and, to the extent possible, the findings from the activities undertaken, is provided to the clearinghouse mechanism, together with the standardized batch identifier, as soon as it becomes available, but no later than one year from the in situ collection date (art. 12 (5)). Once marine genetic resources and digital sequence information is used, including in commercialization, Parties must ensure that the following information, inter alia, is also provided to the clearinghouse mechanism, together with the standardized batch identifier: publications, patents granted and products developed; modalities for the management of access to collected marine genetic

resources and digital sequence information; and details of the sales of relevant products (art. 12 (8)).

Regarding benefit-sharing, the Agreement makes a direct link between benefits and how they should be used by providing that benefits, both monetary and non-monetary, must be shared in a fair and equitable way in order to contribute to the conservation and sustainable use of marine biodiversity of areas beyond national jurisdiction (art. 14 (1)). Regarding non-monetary benefit-sharing, the Agreement provides extensive examples (see art. 14 (2) (a)–(h)). Parties are also required to take reasonable measures to ensure that marine genetic resources and digital sequence information subject to utilization are deposited in publicly accessible repositories and databases as soon as they become available, but no later than three years from the start of such utilization (art. 14 (3)). Reasonable conditions can be placed on access to marine genetic resources and digital sequence information, such as the need to protect the physical integrity of the marine genetic resources and reasonable maintenance and access costs (art. 14 (4)). Furthermore, opportunities for access on fair and most favourable terms may be provided to researchers from developing States (art. 14 (4)). Concerning monetary benefit-sharing, the Agreement provides that such benefits must be shared through the financial mechanism established under the Agreement under article 52, with modalities to be decided by the Conference of the Parties, taking into account the recommendations of the access and benefit-sharing committee to be established under the Agreement (art. 14 (7)).

7. Summary

Marine genetic resources and the use of marine biotechnology hold significant, but as yet untapped, research and development promise. Rapidly advancing techniques will change the research landscape, however, and could greatly support conservation measures, monitoring efforts and the design of MPAs that underpin global commitments for conservation of biodiversity. Research and development of marine genetic resources and marine biotechnology provide a timely opportunity to address urgent global challenges in planetary and human health. If applied in an integrated, inclusive and interdisciplinary way, including through the development of regional marine genetic resource centres of excellence and leveraging existing resources and coordinating input from local, regional and global levels, such efforts have the potential to improve equity in research and, more broadly, across society.

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