Subsection 5A

Subchapter 1C

Medium- and large-scale aquaculture

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Key points

- Digitalization and emerging technologies are playing increasingly important roles in many different parts of aquaculture production.
- Social acceptability issues are emerging in species that were previously accepted, such as molluscs.
- Future development requires meaningful engagement with local communities when planning and managing aquaculture.
- Across all topics there is a need for more detailed and disaggregated data to allow more informed assessments at the local, national and international levels.
- Climate change will bring new challenges throughout the aquaculture value chain, and increased attention needs to be given to climate change adaptation and mitigation.

1. Introduction

Over the past two decades, aquaculture production has increased at a rapid pace, and the sector has become more integrated within the global food system (Naylor and others, 2021). During this time, there have been many changes in farming methods as well as major developments throughout aquaculture value chains, with aquaculture products now among the most globalized food items (Ababouch and others, 2023). Marine aquaculture is a major component of the global aquaculture sector (Food and Agriculture Organization of the United Nations (FAO), 2024b) and an important contributor to food and nutrition security, supplying essential fatty acids, vital nutrients and desirable foods, often with lower environmental impacts than other forms of animal protein production (Tigchelaar and others, 2022). In 2023, the General Assembly adopted resolution 78/69 entitled “Oceans and the law of the sea”, in which it noted the need for actions to support sustainable fisheries and sustainable aquaculture for sufficient, safe and nutritious food, recognizing the central role of healthy oceans in resilient food systems and for achieving the 2030 Agenda for Sustainable Development (United Nations General Assembly, 2023). As part of the ocean and climate change dialogue under the United Nations Framework Convention on Climate Change, it is recommended that national climate policies be linked with blue food production (Cordano and O’Dea, 2023). This emphasis underscores the importance of sustainable marine aquaculture in global food production both now and in the future.

Previous *World Ocean Assessments* had a single chapter dedicated to aquaculture but in the present *Assessment* aquaculture has been divided into a subchapter on small-scale aquaculture (subect. 5A, subchap. 1D) and the present subchapter on medium- and large-scale aquaculture. There are no formal definitions for distinguishing between small-, medium -and large-scale aquaculture: “scale” can refer to a range of production, technological, economic, social and environmental considerations and contexts (Krause and others, 2020). In the present *Assessment*, medium- and large-scale aquaculture refer to commercially oriented production for domestic or export markets, conducted by companies ranging from medium-scale enterprises to large-scale multinational companies. The focus is primarily on sea-based production, such as fish cages or longlines for seaweed and shellfish, as it is directly linked to the ocean, although land-based systems that interact with the marine environment (e.g. seawater use or effluent discharge), including coastal ponds and recirculating aquaculture systems, are also included where relevant. Although sea-based production still relies on more traditional technology, there are other emerging technologies (Føre and others, 2022), including closed and semi-closed containment (Nilsen and others, 2020), submerged production (Sievers and others, 2022) and aquaculture vessels (Long and others, 2024).

There are gaps and discrepancies in how aquaculture data are collected and reported (Kebede and others, 2024). Data sets rarely distinguish between small-, medium- and large-scale aquaculture, and marine production is not easily disaggregated from general aquaculture statistics that also include freshwater and brackish water data. Nevertheless, data from FAO provide an overview of the aquaculture sector (FAO, 2024b, 2024a). According to records classed as marine environment records in the “Global aquaculture production 1950 – 2022” data set in the FAO fishery and aquaculture data platform, marine aquaculture production increased from 55.7 million tons to 60.2 million tons between 2018 and 2022, and the overall value rose from $76 billion to $89.2 billion (FAO, 2024a). There is no noticeable impact on total production from the coronavirus disease (COVID-19) pandemic (FAO, 2024b), but on a finer scale, the actual consequences of the pandemic were more complex, with challenges for some companies but opportunities for others (Nielsen and others, 2023).

The aim of the present subchapter is to provide an overview of the current status of medium- and large-scale marine aquaculture and put forward a vision for the future. The first three parts of the subchapter (on pressures and impacts, socioeconomic aspects, and governance) are focused on the assessment period for the third *World Ocean Assessment*, covering the years 2018 to 2023. The final part (on sustainability pathways) considers what future decades up to 2050 could look like under a business-as-usual scenario and identifies potential actions for a more sustainable future.

2. Pressures and impacts

Most medium- and large-scale aquaculture takes place within a few km of the coastline (Papageorgiou and others, 2021; McIntosh and others, 2022; Liu and others, 2023; Harvey and others, 2024), but new technologies, industry expansion and intensification are changing how aquaculture utilizes ocean space (Bjelland and others, 2024; Buck and others, 2024), and changes are not homogenous around the world. In China, according to estimates, the area used for marine aquaculture in 2020 was almost three times greater than in 2010 (Liu and others, 2023). In the Mediterranean, however, over a similar period, the total number of cages increased only very slightly, but the number of small cages decreased, and there was an increase in the number of medium and large cages (Papageorgiou and others, 2021). In many areas, coastal space is becoming increasingly scarce (Sanchez-Jerez and others, 2016) and conflict with other marine users has been highlighted as a constraint to further the development and expansion of marine aquaculture (Galparsoro and others, 2020). Marine spatial planning and zoning are frequently promoted to manage conflict over space and resources, but the lack of data, insufficient tools and poor governance are barriers in some locations.

Climate change also brings challenges for aquaculture production and the wider supply chain (Stavrakidis-Zachou and others, 2021; Fuentes-Santos and others, 2021; Falconer and others, 2022; Kim and others, 2024). Over the assessment period, there are examples of studies describing climate-related events affecting marine aquaculture, including marine heatwaves in the Mediterranean (Atalah and others, 2024), harmful algal blooms in Chile (Soto and others, 2021), storms in Viet Nam (Pham Thai and others, 2023) and typhoons in China (Li and others, 2024; Yin and others, 2024). Since the frequency and intensity of climate stressors are projected to increase over the next decades (Intergovernmental Panel on Climate Change (IPCC), 2023), there will be implications for future planning of the sector. There is increasing emphasis on the need for aquaculture companies to monitor their own contributions to climate change and implement mitigation measures throughout the entire value chain to reduce emissions (Jones and others, 2022). Studies have shown that feed production (MacLeod and others, 2020) and transport to market (Ziegler and others, 2024) are among the highest contributors to greenhouse gas emissions. Knowing where emissions occur along the value chain will allow the sector to act. Ziegler and others (2024), for example, estimated a 10% reduction in farmgate emissions for 1kg of Norwegian salmon between 2017 and 2021 due to changes in feed ingredients.

Since the publication of the second *World Ocean Assessment*, increased attention has been given to low-trophic marine species, including large-scale farming of molluscs and seaweed. Low-trophic farming is one of the oldest types of aquaculture and is a large contributor to total production (FAO, 2024b, 2024a), but the renewed focus promotes further expansion to meet demands for sustainable food production (Krause and others, 2022). However, it is also recognized that there are many challenges that need to be addressed if large-scale low-trophic aquaculture is to significantly increase, especially as some parts of the world have been experiencing stagnation or declines in the production of low-trophic species (Avdelas and others, 2021; Botta and others, 2020). One of the main barriers in many areas is the availability of farming locations that can provide sufficient resources to sustain large-scale production over many years. In the case of mussels, challenges with wild seed supply have been reported in Spain (Padin and others, 2024), New Zealand (Skelton and others, 2022) and Chile (Molinet and others, 2021). At present, mussel hatcheries are unable to meet the demands of the sector as they are too small-scale, not cost-effective or not permitted by the authorities (Avdelas and others, 2021; South and others, 2022). Trials are under way to improve the efficiency of collectors (van Broekhoven and others, 2024) and increase seed retention using management techniques (Reyden and others, 2024). In Chile, mussel collectors seem to be extremely efficient, although there are concerns about the potential impact of overfishing of larvae (Molinet and others, 2021).

For fed aquaculture (e.g. fishes and shrimps), concerns remain over the use of marine ingredients (fishmeal and fish oil), the overexploitation of wild stocks (Colombo and others, 2023; Eroldoğan and others, 2023) and feed-food competition (van Riel and others, 2023) (see subect. 5A, subchap. 1A). Over the past three decades, there has been a significant reduction in the proportion of marine ingredients in aquaculture feeds, particularly salmon feed (Aas and others, 2022). Since the publication of the second *World Ocean Assessment*, despite considerable research and development efforts, there have been no major breakthroughs. Research is focusing on alternative ingredients such as insect meal, single cell proteins and microalgae (Colombo and others, 2023; Glencross and others, 2024) but in 2020 only 0.4%

of salmon feed ingredients were from such sources (Aas and others, 2022). The use of alternative ingredients is very likely to increase in future years for salmon and other species (Albrektsen and others, 2022; Colombo and others, 2023), but there are many factors that will affect the rate at which it will happen, and this field of research is very dynamic since feed is a major expense during the farming cycle (Iversen and others, 2020).

Over the assessment period, the use of digitalization and precision fish farming techniques increased (Føre and others, 2018, 2024) in order to optimize feeding practices (for example, Georgopoulou and others, 2024), helping to reduce environmental impacts (Mustapha and others, 2021). For traditional cages, the collection of waste remains challenging and is rare in commercial settings due to the volume of waste and the depths involved. Waste collection is likely to be more feasible in semi-closed or closed containment systems (Schumann and Brinker, 2020; Føre and others, 2022), as well as in recirculating aquaculture systems (Sánchez and Checa, 2023), although most of these systems are still in their infancy and not a significant part of commercial-scale production. Integrated multi-trophic aquaculture, in which non-fed species such as bivalves and seaweed utilize the waste from fed species like finfish, has also been identified as a potential route to increase production and reduce environmental impacts, but there are limited examples of commercial-scale integrated multi-trophic aquaculture farms due to planning, regulatory and operational barriers (Stenton-Dozey and others, 2021; Sickander and Filgueira, 2022). However, there is potential for a more regional approach to integrated multi-trophic aquaculture and for landscape-scale or water body-scale integration (Sanz-Lazaro and Sanchez-Jerez, 2020), as seen in Chile, where large-scale salmon farming occurs in the same areas in which intensive mussel farming takes place (Camelo-Guarín and others, 2021).

During the assessment period, considerable attention has been given to antimicrobials and to the potential for antimicrobial resistance due to its implications for human health (Reverter and others, 2020; Schar and others, 2020; European Food Safety Authority and others, 2024). In 2015, States Members of the United Nations committed to producing national action plans for antimicrobial resistance and, by 2020, many of the major aquaculture-producing States had included aquaculture within such plans (Caputo and others, 2023). Significant efforts over the past decade have been focused on reducing antimicrobial dependency in aquaculture (Bondad-Reantaso and others, 2023). Alternative prevention and therapeutic strategies have been developed, including vaccination (Barnes and others, 2022), functional feeds and phage therapy, a natural, targeted biocontrol method using species-specific bacteriophages (viruses of bacteria) to treat bacterial infections, offering an alternative to antibiotics (Kalatzis and others, 2018). However, these methods face challenges in large-scale adoption due to high development costs and strict regulatory requirements. Therefore, although some countries are seeing a decline in antimicrobial use, usage is increasing in others (Lulijwa and others, 2020). Further work is needed to achieve the recommendations and standards set by international organizations and certification schemes (Luthman and others, 2024), and a critical issue is the need for more reliable data, particularly in the shrimp sector (Thornber and others, 2020).

Escapes from farms are a concern, as they represent an economic loss to producers and can also have adverse ecological impacts, such as interbreeding with wild populations and spreading disease to wild populations (Sawayama and others, 2019; Atalah and Sanchez-Jerez, 2020). It is difficult to determine the status of aquaculture escapes since many countries do not have formal reporting requirements, and surveillance schemes are often inadequate or absent (Soto and others, 2023; Toledo-Guedes and others, 2024). In the Mediterranean, escapes of Gilthead seabream (*Sparus aurata*) have been significantly correlated with seabream landings from fishing vessels, suggesting that escapes contribute to this type of fishery (Toledo-Guedes and others, 2024). In some locations, there have been reductions in the number of escapes. For example over the past two decades there has been a significant effort in Norway to reduce escapes through strict regulations and technical standards (Afewerki and others, 2023), and recent estimates suggest that about 0.04% of Norwegian farmed salmon are registered as escapes (Føre and Thorvaldsen, 2021). In Norway, there have also been considerable efforts to develop and use triploid salmon that are sterile and unable to reproduce, but there are challenges in their use (de Fonseka and others, 2022) and in 2023, due to welfare concerns, the Government of Norway announced that it would not allow the use of triploid salmon in food fish production.[1] Escape concerns are often greater where non-native species are used (Soto and others, 2023), as escaped species can become invasive, outcompeting local species and affecting ecosystem structure and functioning. A recent worldwide assessment revealed that approximately 26% of marine fish production involves species that are not native to their marine ecoregion (Atalah and Sanchez-Jerez, 2020).

3. Socioeconomic aspects

Compared with the years covered by the first and second *World Ocean Assessments*, the period from 2018 to 2023 saw a lot more attention paid to aquaculture in the media (Condie and others, 2022; Machado and others, 2023; Sutherland and Armbrecht, 2024). Negative media articles were focused on salmon production and its environmental effects more than on any other species. In some cases, previous high-profile events, such as environmental problems in Macquarie Harbour in Tasmania, Australia, leading to an increased public focus on environmental sustainability and governance, caused this uptick (Condie and others, 2022). Mainstream media tended to be more negative in developed countries than in developing countries (Budhathoki and others, 2024). Local settings influence the portrayal, limiting the ability to make generalizations; for example, in New Zealand, it has been suggested that the tendency towards negative media portrayals occurs as the industry reaches maturity (Condie and others, 2022), whereas in Atlantic Canada social acceptability increased with the age of the industry (Kraly and others, 2022).

Strongly linked to changing public perceptions of aquaculture, in the period 2018–2023 (and starting in the years just preceding), the concept of a social licence to operate became firmly embedded in societal discussions on commercial aquaculture, as well as being evident in government policy and industry strategy (Alexander, 2022). Efforts to explore the use of social licences to operate for aquaculture products has primarily been focused on salmon (e.g. Weitzman and others, 2023; Eriksen and Mikkelsen, 2024; Olsen and others, 2024) and seaweed (e.g. Billing and others, 2021; Rostan and others, 2022). A key finding across these studies is that social licences to operate are local in nature, and the need for efforts to secure and maintain such licences should be adapted to the local context.

The importance of understanding the broader social impacts of aquaculture is also coming to the fore and includes aspects such as the consideration of livelihoods and human development, human rights, social and cultural needs, flow-on economic benefits and improved infrastructure, among other issues (Alexander and Kelling, 2024). However, data are lacking in relation to many of these aspects (Krause and others, 2020; Mikkelsen and others, 2021), making it difficult to assess what has changed in the 2018–2023 period. What is known is that social and human concerns are insufficiently addressed in the

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[1] See www.regjeringen.no/no/dokumenter/meld.-st.-8-20242025/id3080297.

aquaculture sector (Brugere and others, 2023). An example is the increasing awareness of the need to address gender equality in the aquaculture sector (see also subsect. 5B, chap. 6), aligning with the Sustainable Development Goals (Troell and others, 2023), but assessment of gender-related issues in the aquaculture sector is difficult due to the lack of gender-disaggregated data (Kruijssen and others, 2018; Gopal and others, 2020; Brugere and others, 2023; Troell and others, 2023). Nevertheless, research has shown that female practitioners in the aquaculture industry chain face issues related to worker safety and unequal pay, as well as constraining gender norms and discrimination (Rao and others, 2024).

Data suggest that aquaculture employment may have decreased slightly globally during the period under review, although the picture on a regional basis shows significant increases in Latin America and the Caribbean and a decrease in Asia (FAO, 2024b). In Europe, Northern America and Oceania, which are primarily focused on large-scale commercial aquaculture, employment figures have remained stable. The traditional skills required for employment in the sector are not easily transferable as new technologies such as sensors, big data, machine learning and artificial intelligence have become more prominent (McDonald and others, 2024). It is not clear if this digital capability training was under way between 2018 and 2023, although during this period the European Union launched the "Blue careers for a sustainable blue economy" programme aimed at developing the next generation of blue skills for sustainable maritime careers (European Commission, 2022).

The social considerations associated with aquaculture also extend to working conditions. Globally, several occupational health and safety problems are prevalent among aquaculture workers, including ergonomic hazards, musculoskeletal complaints, diseases and injuries (Fry and others, 2019; Kaustell and others, 2019; Mitchell and Lystad, 2019; Moreau and Neis, 2009; Myers, 2010; Ngajilo and Jeebhay, 2019; Watterson and others, 2020). Norwegian studies of salmon farming have found that employees worry about strain and injuries and that organizational challenges related to goal conflicts, work pressure and employee participation can be found (Kongsvik and others, 2018; Thorvaldsen and others, 2020). As the mitigation of these risks has received little attention globally, researchers have called for a global commitment for occupational health and safety in aquaculture (Cavalli and others, 2019). Working conditions for aquaculture workers were also a topic at the sixth International Fishing Industry Safety and Health Conference, held in January 2024, which was aimed at helping to advance safety and health research and increase awareness of safety and health issues in fishing, aquaculture and seafood processing (Lincoln and others, 2024). Sadly, human rights abuses can be found everywhere, but during the period 2018–2023 issues faced in the aquaculture sector increasingly became an issue, with certification schemes particularly being challenged by third-sector organizations such as charities and non-profit organizations (see, for example, Human Rights at Sea, 2023). Making the headlines, a 2024 report, based on data collection commencing in 2021, detailed pervasive systematic abuse throughout the Indian supply chain, including the exploitation of vulnerable workers, forced labour and dangerous conditions (Corporate Accountability Lab, 2024).

Over the assessment period, increased attention was given to sustainable food production and the societal benefits of different food types. With increasingly stringent constraints on terrestrial land use driven by climate change and biodiversity conservation, a well-managed ocean is poised to become a primary source of food to meet humanity's growing demand, and marine aquaculture will account for most of this growth (Costello and others, 2020). Seafood provides the most dominant source of omega-3 long-chain polyunsaturated fatty acids and holds significant potential to reduce micronutrient deficiencies (Golden and others, 2021). In addition, many forms of marine aquaculture have a smaller environmental footprint than industrial meat production, especially red meat, which has significantly higher resource demands (Gephart and others, 2021). There are also calls to recognize the range of purposes that aquaculture can have beyond food production (Mizuta and others, 2023). For example, the rise of stock enhancement aquaculture has aided in the recovery of some wild fish populations, as evidenced by the initial success of large yellow croaker population recovery in Chinese coastal waters (Yuan and others, 2021). Furthermore, ocean-reliant communities worldwide are facing increasing pressures to shift their livelihoods, and marine aquaculture provides a reliable alternative livelihood source (Gentry and others, 2020). Low-barrier entry aquaculture practices enable persons in marginalized situations, often women, who previously lacked access to means of production, to directly participate in production, thereby improving gender equality (McClenachan and Moulton, 2022; Wurmann and others, 2022).

4. Governance

Aquaculture governance is paramount to securing sustainable production and industry, but has been implemented in different ways across the globe (Naylor and others, 2023), with public regulation ranging from being starkly absent to highly present. Public governance of aquaculture requires scientifically founded regulation that is adaptable and flexible in relation to the type of aquaculture present and its development, capable of nurturing the abilities of the private sector, public regulators and non-governmental organizations (NGOs) alike, and in a manner that supports control, transparency and accountability (Ababouch and others, 2023). FAO guidelines for assessing legal frameworks for aquaculture support such an approach while identifying the necessary regulatory mechanisms for advancing sustainable aquaculture (Hodgson, 2023). Between 2016 and 2018, Galparsoro and others (2020) conducted a large-scale global stakeholder consultation to identify the major obstacles preventing the development and expansion of marine aquaculture, and found that almost 40% of the responses were related to administrative challenges, including licensing and regulation. A literature review also found that complicated and fragmented approaches to planning and licensing were frequently highlighted as barriers for marine aquaculture expansion (Falconer and others, 2023). Studies have also emphasized that many existing regulatory frameworks may not be suitable for new technologies, alternative locations or innovative production methods, including farming in more exposed or offshore waters (Davies and others, 2019; Watson and others, 2022; Krause and others, 2024).

Since the publication of the second *World Ocean Assessment*, there have been examples of proactive governance initiatives to encourage responsible aquaculture development at the national and international levels. A notable international development was the adoption of the Guidelines for Sustainable Aquaculture in 2024 (FAO, 2025), a framework aimed at helping States Members of the United Nations and stakeholders to develop and intensify aquaculture sustainably. The guidelines were prepared by FAO and are aligned with the 2030 Agenda for Sustainable Development and the relevant Sustainable Development Goals (UN General Assembly, 2015), as well as other key policies and agreements. At a more regional scale, the FAO General Fisheries Commission for the Mediterranean (GFCM) has taken significant steps to support the Mediterranean and Black Sea aquaculture sector. The Commission’s 2030 Strategy (FAO, 2021), which is aligned with the Sustainable Development Goals, envisions a sustainable, resilient and fully realized sector. As Mediterranean aquaculture-producing countries generally adhere to a vertically integrated system of legal requirements established at the national, European Union, subregional and Mediterranean levels (Papageorgiou and others, 2021), the Commission plays a crucial role in guiding this sector. Effective governance is encouraged through enhanced collaboration with the Commission's contracting parties and cooperating non-contracting parties (FAO GFCM, 2025) alongside stakeholders, to create supportive legal and administrative frameworks. Ensuring sustainability also depends on effective spatial planning, embracing digitalization – namely the integration of digital technologies, data analytics and automation (Internet of Things, sensors, artificial intelligence, remote monitoring systems and big data analytics) – to support data-driven decisions, and promoting diversification towards a lower environmental impact. Knowledge-sharing is facilitated through dedicated demonstration centres, and the creation of technical advisory groups under different thematics, such as animal health and welfare or innovation and technology, are enabling the involvement of experts and the dissemination of actions.

During the assessment period, there were several notable actions within the salmon farming sector that could affect where and how salmon are produced, including changes in tax regimes (Misund and others, 2024) and regulatory restrictions in some locations (Mather, 2024). Such interventions have been driven by a complex interplay of rights holders and stakeholders in the management of aquaculture and balancing environmental concerns and socioeconomic impacts. Since these are recent developments, the consequences are inconclusive at present.

Alongside national regulation, private certification schemes have emerged as a response to the perceived inefficiency of public regulation, mainly for securing transparency in and access to a global market. Certification schemes act as a mechanism to increase transparency and accountability across different producers. Recent years have seen the number of schemes increase in parallel with an expansion of potential applications and increased uptake. The Aquaculture Stewardship Council is an example of a certification scheme. Globally the number of farms certified by the Council almost tripled during the reporting period, from 800 in 2018 to 2,085 in 2023, and there is reason to believe that other schemes have also increased in use. However, data on the proliferation of most schemes are not made public, and comparisons are difficult across schemes as the entity certified ranges from production sites to entire companies. Schemes may serve as decision-making information to investors, politicians and public authorities, as risk-reducing mechanisms for retailers, or as a filter distinguishing between sustainable and unsustainable choices for consumers, and they provide access to markets and price premiums for producers (Bush and others, 2013; Bush and Oosterveer, 2015; Olsen and others, 2021; Tlusty, 2012). Topics relevant for various schemes are food safety risks, the degree of sustainability, fish welfare practices, working conditions, transparency and many others. However, the specific definitions of sustainability as promoted by different schemes are often strongly skewed towards environmental topics and food safety, and less towards socioeconomic sustainability (Osmundsen and others, 2020). Recently, schemes such as the Aquaculture Stewardship Council appear to be strengthening their standards in social and ethical domains.

The impact of certification on sustainability is hard to evaluate, but there is reason to believe that the development still follows the progress identified by Naylor and others (2021) in that environmental performance is improving as a response to increased regulation, including private certifications. Following the increased recognition of certifications, there is great variation in how assessments are carried out, ranging from desktop ratings on a narrow set of indicators to multiple onsite visits by professional auditors looking into every aspect of production. Some schemes intend to give companies incentives to improve their practices and require improvements from audit to audit. While private certification schemes are often portrayed as voluntary mechanisms, they are de facto mandatory as purchasers and certain markets expect producers to comply with specific schemes, emerging as a corporate social responsibility strategy (Rector and others, 2024). The high number of labels and certification may cause confusion and label fatigue among consumers, thus weakening the effect of stimulating sustainable food choices. Other concerns relate to how certification may act as a barrier to trade for smaller companies or companies from developing countries that cannot afford the costs and documentation requirements (Bush and others, 2013). Certifications are often expensive to attain, and multiple certifications are required when targeting different markets (Amundsen and Osmundsen, 2020). Furthermore, global certification schemes catering for an international market may be disconnected from local sustainable practices and knowledge (Jolly and others, 2023; Little and others, 2018). The creation of standards that reflect the interests of consumers rather than local aquaculture production realities may shift focus away from practices that are sustainable in a local context.

5. Sustainability pathways

Medium- and large-scale marine aquaculture will play an increasingly important role in future food and nutrition security, so it is important to identify factors that support sustainable and responsible development and reduce negative impacts (Crona and others, 2023; Tigchelaar and others, 2022; Willett and others, 2019). Scenario analysis is a tool to identify pathways to a healthy and productive ocean in the future (Nash and others, 2022; Pecl and others, 2022), including aquaculture (Couture and others, 2021; Farmery and others, 2022). Here, scenario analysis is used to describe two potential pathways for medium- and large-scale marine aquaculture and link directly to the Sustainable Development Goals and contribute to a more sustainable ocean in 2050. The business-as-usual pathway describes a plausible future that is likely to occur based on current trends, in the absence of any major interventions or shocks. In contrast, the sustainable future pathway describes a more sustainable future that could occur with deliberate actions that change the current trajectory. Using information on the present status of medium- and large-scale aquaculture from the previous three parts of the present subchapter, together with information from the regional workshops held in preparation for the third *World Ocean Assessment*, two key drivers of change are identified: governance and regulation; and skills and capacity-building. The PESTLE (political, economic, societal, technological, legal, environmental) framework is then used to identify actions that could support the move to a more sustainable future (see table). The approach was adapted from the more comprehensive Future Seas 2030 project (Farmery and others, 2022; Nash and others, 2022; Pecl and others, 2022). These examples could be further developed by States Members of the United Nations and aquaculture stakeholders to create more detailed sustainability pathways using context-specific information.

Business-as-usual scenario

The industry continues to expand using existing farming methods as well as new technologies, novel production methods and new locations, contributing to achieving zero hunger (Sustainable Development Goal 2). Regulatory systems are improving but are still slow to reform compared with the pace of technological development, which limits overall production potential. Insufficient progress is made on environmental and social impacts across all forms of the production system due to reliance on outdated monitoring and assessment methods. While certification schemes start to move the industry towards more sustainable outcomes (Goal 12), they continue to be incremental and occur only in more sustainabilityminded corporations. A lack of skills and capacity training leads to a decreasing and disillusioned workforce as traditional skills cannot be transferred to newer technologies and locations.

Sustainable future scenario

The industry continues to expand using existing farming methods as well as new technologies, novel production methods and new locations, contributing to achieving zero hunger (Goal 2). Significant financial investments in new and revised regulatory frameworks provide a more holistic and evidence-based approach to aquaculture licensing, increasing transparency in planning and management decisions for all stakeholders and the public. Environmental and social impacts are reduced due to innovative monitoring and revised approaches, which consider the system holistically (addressing Goals 12, 13 and 14). Certification schemes push the sector above and beyond compliance requirements, leading to increasingly sustainable and responsible production (Goal 12). Government and industry-incentivized capacity-building schemes provide decent work opportunities that keep pace with industry development (Goal 8).

Table

Potential actions for each driver of change that could accelerate progress towards a sustainable future scenario in which medium- and large-scale marine aquaculture contributes to increased production of high-quality protein in a responsible manner and supports decent work and economic growth

PESTLE category	***Governance and regulation***	***Skills and capacity-building***
Political	Produce novel governance frameworks that incentivize sustainable development, collaboration and transparency. Minimize potential conflicts of interests within government agencies, i.e. as promoter and regulator.	Establish and support initiatives that facilitate transdisciplinary co-production, sharing of knowledge and international cooperation related to new technology, novel production systems and governance.
Economic	Provide financial support to address bottlenecks in licensing and regulatory frameworks through streamlined administrative procedures. Financial support should also be used to update existing regulations or develop new licensing frameworks for novel farming systems. Improve collection and analysis of disaggregated economic data to support more informed assessments and improvements in governance and regulation.	Allocate financial support for capacity-building and skills training throughout the industry and associated activities. Include schemes that will enable upskilling and retraining in new technologies and novel production systems. Improve collection and analysis of disaggregated workforce data to support targeted financial support for capacity-building where required.
Societal	Co-develop marine spatial planning strategies with other activities, local	Increase awareness of the roles, experience and skills required in

	stakeholders and communities to ensure trust, procedural fairness and redistribution of profits. Enable processes that minimize conflicts with other ocean users. Promote aquaculture literacy. Improve the collection and analysis of disaggregated social data, including better data on gender, to support more informed assessments and improvements in governance and regulation.	aquaculture, e.g. precision farming. Ensure that training programmes emphasize occupational health and safety. Provide accessible career mentoring schemes for new entrants, returners and the long-term workforce.
Technological	Incentivize novel and improved farming systems, particularly in new areas, e.g. the open ocean, that optimize species health and welfare, are safe for workers and reduce negative effects on the environment.	Create infrastructure to support capacity-building and skills training. Enhance collaborative opportunities for data collection, analysis and sharing to inform decision-making. Strengthen access to educational resources such as digital content. Support hatcheries and breeding programmes.
Legal	Revise licensing and regulatory frameworks to address bottlenecks based on evidence, ensuring that regulations are adjusted to fit the scale and risk of the farming operation. Develop and revise legal frameworks for novel farming systems. Provide legal mechanisms to co-develop marine spatial planning strategies with other activities, local stakeholders and communities.	If required, develop enabling legislation to support relevant infrastructure to support capacity-building. Develop training schemes to support the implementation of health and safety regulation. Ensure that cross-sectoral training schemes align with regulatory requirements for marine spatial planning.
Environmental	Promote environmental data collection and analysis, including climate change modelling, to enhance site selection to minimize antibiotic and chemical use and interactions with wild species (through escapes or diseases), and to reduce carbon dioxide (CO_2) emissions.	Organize exchange programmes that facilitate visits and placements across the aquaculture sector, including existing and new technology, for industry, researchers, policymakers, external stakeholders and wider society. Ensure that there are knowledge exchange opportunities with other sectors to improve marine spatial planning.

Source: Prepared by the writing team.

Below are some of the “governance and regulation” and “skills and capacity-building” actions suggested in the table that Member States could use to help to move towards the sustainable future scenario. The ability to implement such initiatives, and the associated timescales, will depend on the aquaculture-specific context in each Member State.

Governance and regulation

A sustainable future relies on governance and regulatory frameworks that have strong social credentials, generated through greater trust and transparency among all actors and a better understanding of how aquaculture operates within the environment and overall societal contributions. Ocean literacy has been defined as a catalyst that can accelerate systemic change and support sustainability goals (McKinley and others, 2023). In a similar way, aquaculture literacy could be a route to increased understanding of the role and responsibilities of aquaculture within the marine environment and how this links to other activities, which could then strengthen governance and regulatory frameworks. In Norway, several initiatives are aimed at increasing public knowledge of aquaculture, including visitor centres and a web-portal that includes facts, data and information for the general public (Mikkelsen and others, 2021).

Governance and regulation must be underpinned by scientific evidence as this increases legitimacy and trust in the rules and practices that are implemented. In this sense, the use of precision farming techniques (Føre and others, 2018) and large-scale monitoring, supported by remote sensing and satellite data integration, will be crucial for predicting conditions not only in farms but also in aquaculture zones (Chatziantoniou and others, 2023), allowing better planning for aquaculture and better coordination with other activities, optimizing the use of space and resources, such as through marine spatial planning. In addition, increased dialogue and knowledge-sharing between sectors and marine users will lead to better understanding of requirements for marine space across all user groups to support the co-development of plans that reduce conflict. Digitalization of the aquaculture sector will support evidence-based co-development of spatial management plans and strategies with other activities and communities. Vast amounts of data collected at farms will provide greater insight into climate change for all marine activities (Falconer and others, 2025). Better understanding of the farming environment will allow for the development of adaptive management strategies, such as early warning systems and flexible farm designs, to increase resilience to climate change (Sanchez-Jerez and others, 2023). Where possible, climate adaptation measures should be mainstreamed into aquaculture planning and practices, especially in regions that are vulnerable to marine heatwaves and algal blooms.

Skills and capacity-building

The pressing need for increased amounts of responsibly produced food requires a significant boost in production at a rapid pace, which in turn demands a ready workforce equipped with the necessary knowledge, skills and experience. The aquaculture sector must consider new and innovative ways to attract new entrants and support the existing workforce in both reskilling and upskilling. Lifelong learning will be important for increased resilience in the future workforce, supported by fair and equitable access to new knowledge and training opportunities. Networking initiatives such as Women in Scottish Aquaculture could provide routes to mentoring and career support for new entrants, returners and the longer-term workforce (Kelling and Lawan, 2023).

Transformative change rarely occurs in silos, so actions are required that will support diverse and inclusive knowledge exchange and co-learning opportunities (Partelow and others, 2023). However, research infrastructure is expensive to install and maintain, which can exclude parts of the sector and limit the potential for upskilling or new knowledge generation. Within the research and innovation landscape, a European Union-funded project (AQUAEXCEL3.0, 2023) is an example of a mechanism that encourages new partnerships and widens access to research infrastructure that would otherwise be unavailable to many individuals and groups.

Aquaculture companies that intend to develop in more remote offshore locations will require more robust structures, advanced technologies and production systems with increased automation and reduced maintenance needs. There may be opportunities to cooperate with other sectors, sharing knowledge and research infrastructure. For example, the Government of Australia has partnered with industry and academia to establish the Blue Economy Cooperative Research Centre, a 10-year funded initiative that supports research and training initiatives across aquaculture, offshore engineering and renewable energy (Blue Economy Cooperative Research Centre, 2022).

5. Conclusion

Medium- and large-scale aquaculture is an important part of the ocean economy and an essential contributor to food and nutrition security. Since the publication of the second *World Ocean Assessment*, production has increased, but there are still bottlenecks and challenges that need to be addressed if the sector is to significantly increase production and contribute further to sustainability goals. Data gaps and the lack of consistent reporting across species, systems and locations is an issue that makes it difficult to understand the scale and importance of some topics. Nevertheless, across the sector there are many examples that show how innovative solutions have been used to address previous challenges.

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