



Offshore aquaculture, present and future

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Abstract. The role of fish production in global food security is underscored by increasing demand, which in the future is expected to be met largely through aquaculture. Worldwide, available water surfaces and volumes are becoming increasingly limited, while coastal areas are subject to intense demand and exploitation. Consequently, sustainable solutions are being sought for the development of aquaculture in exposed offshore areas. Marine aquaculture is conducted in accordance with the legal frameworks applicable in different regions. The growing interest of farmers, investors, and governments in several countries and regions (Norway, Chile, China, the EU, the USA, etc.) in expanding aquaculture in seas and oceans necessitates the establishment of appropriate legal frameworks, as well as clear directions and guidelines. By integrating activities from various sectors with fish or seafood farming at the same offshore locations, significant economic, technical, and environmental advantages can be achieved.

Key Words: aquaculture, extensive areas, oceans, seas.

Introduction. The significant contribution of fisheries and aquaculture to the global economy and to food security worldwide is now widely acknowledged (OECD 2025). Current estimates indicate that nearly 600 million people derive their livelihoods, in whole or in part, from fisheries and aquaculture activities (FAO 2022; OECD/FAO 2024). Globally, more than 200 million tonnes of aquatic animals and algae are produced through capture fisheries and aquaculture, and demand for these products for human consumption continues to rise steadily (World Bank 2013; FAO 2022).

A substantial share of global fish production is supplied by aquaculture, which is projected to account for more than 55% of total production by 2033 (OECD/FAO 2014). While capture fisheries are widely regarded as unsustainable, aquaculture has experienced consistent growth over the past three decades (Costello et al 2020; FAO 2020; OECD 2025). Nevertheless, this growth has slowed in recent years compared with the previous decade, largely due to several challenges currently facing the sector, including increasing levels of production intensification under sustainability constraints, limited opportunities for expansion in marine environments, and the emergence and spread of pests and diseases (FAO 2018; Morro et al 2022; OECD/FAO 2024; Oddsson 2020; Wang et al 2022).

The world's seas and oceans play a critical role in the supply of fish products, and marine aquaculture—commonly referred to as mariculture—represents a key opportunity to substantially increase global food production in the coming years (Costello et al 2020; Falconer et al 2023). According to FAO statistics, 63% of total fish production originates from marine waters, comprising 70% from capture fisheries and 30% from aquaculture, while the remaining 37% is derived from inland waters, where aquaculture accounts for 83% and capture fisheries for 17%. The same source reports that, in 2022, mariculture produced 71.7 million tonnes of aquatic animals and algae, with marine fish farming contributing approximately 65% of this output (FAO 2018, 2022, 2024).

Competition among economic activities for limited land and freshwater resources, together with the growing demand for fish species and marine aquatic products, is driving investors and producers to identify and develop new locations for aquaculture in marine and oceanic environments (Lovatelli et al 2013; Cardia & Lovatelli 2015; Wang et

al 2022). This shift enables large-scale production of fish and seafood and, by moving operations farther offshore, helps mitigate a range of social, economic, and environmental challenges associated with nearshore aquaculture (Bostock et al 2010; Knapp 2013; Gentry et al 2016; Naylor et al 2021).

The expansion of aquaculture into marine and oceanic environments necessitates careful consideration of environmental risks, as well as technical challenges related to the design and construction of structures and enclosures for rearing aquatic organisms. Offshore aquaculture operations also entail higher costs and logistical constraints, including increased transportation requirements and more limited access to services, supplies, processing, and product utilization. In parallel, there is a clear need for legislative frameworks and spatial planning systems that are aligned with these requirements to support the sustainable development of aquaculture in marine and oceanic areas. In this context, and drawing on existing theoretical and applied research as well as recent advances in the field, this paper highlights key general aspects of offshore aquaculture.

The terminology used in the literature to describe offshore aquaculture reflects the implementation of specific activities in locations situated far from the coast, under conditions characterized by strong currents and wave exposure, and involving specialized facilities, equipment, and maintenance vessels, while also accounting for applicable legal and regulatory frameworks (Kapetsky et al 2013; Knapp 2013; Ferreira et al 2014; Morro et al 2022).

According to the FAO Technical Workshop (2010), aquaculture is classified as offshore when production systems are located at considerable distances from the coast (typically more than 2 km), in deep waters (exceeding 50 m), and under highly exposed conditions characterized by large waves (over 5 m), strong ocean currents, variable winds, and high storm intensity. Such environments generally require remote monitoring and operations (Lovatelli et al 2013; European Commission 2021).

In delineating different types of aquaculture, Knapp (2013) emphasizes the wide range of technological, environmental, and regulatory factors involved, which vary across countries and regions. Accordingly, the term inshore is used to describe aquaculture conducted closer to the coast in relatively sheltered areas, whereas offshore refers to aquaculture operations situated farther from shore in more exposed marine environments.

Beyond the specific characteristics of ocean environmental conditions, Wang et al (2022) highlight the diversity of terms used to define offshore aquaculture, reflecting the perspectives of different stakeholders, including producers, public regulatory authorities, national and international agencies, technology providers, and researchers.

The strategic importance of the sector, combined with the complexity of the factors involved, underscores the need for a harmonized terminology to facilitate the identification of suitable locations and to support effective planning and implementation of offshore aquaculture across different regions (Holmer 2010; Morro et al 2022; Buck et al 2024).

Advantages and Disadvantages of Offshore Aquaculture. Offshore aquaculture presents both advantages and disadvantages. By relocating fish farming systems to areas with minimal competition from other human activities—such as urban development, tourism, recreation, and capture fisheries—many spatial and user conflicts can be avoided. In addition, the availability of larger surface areas and greater water volumes enhances waste dispersion and reduces environmental pressures, thereby lowering the risk of disease outbreaks (Bostock et al 2010; Wang et al 2022).

Offshore aquaculture is associated with a range of challenges that must be carefully identified and assessed (Ferreira et al 2014). Environmental variability and limited accessibility to remote locations contribute to reservations among producers and investors regarding the relocation of aquaculture activities to offshore areas (Wang et al 2022). Beyond the environmental risks affecting fish welfare, aquaculture systems must be securely and stably positioned to enable routine operations and ensure safe working conditions (Shainee et al 2013). The dynamic conditions of offshore environments—

including strong currents, waves, storms, and seismic events—are therefore critical determinants in the structural design and resilience of aquaculture installations. Failure to adequately address these factors may result in structural damage or total system failure, leading to fish escapes and, in extreme cases, loss of human life (Morro et al 2022).

The Need for International Regulations. The wealth of the world's seas and oceans has historically generated international conflicts, and the unsustainable exploitation of aquatic resources prompted the United Nations to adopt the United Nations Convention on the Law of the Sea (https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf). This convention defines the boundaries of territorial waters and the exclusive economic zone, while areas beyond these limits—commonly referred to as offshore—lack a formal legal definition (Ferreira et al 2014). Maritime Spatial Planning (MSP) serves as a key tool for the responsible use and sustainable management of the global ocean (<https://www.ioc.unesco.org/en/marine-spatial-planning>; https://oceans-and-fisheries.ec.europa.eu/ocean/blue-economy/maritime-spatial-planning_en).

Marine spatial planning (MSP) is an ongoing process, with implementation underway or already in practice in several regions around the world (Kite-Powell 2017). By organizing and managing maritime space, MSP provides numerous benefits, including the reduction of conflicts and the promotion of synergies between different activities, the encouragement of investment, the development of cross-border cooperation, and the protection and conservation of the marine environment (eur-lex.europa.eu/legal-content/RO/TXT/PDF/?uri=CELEX:32014L0089).

Globally, the fisheries sector faces numerous uncertainties related to climate change and evolving regulatory frameworks, and the sustainable development of aquaculture necessitates corresponding governance reforms (FAO 2022, 2024). The growth potential of offshore aquaculture depends largely on the profitability of investments, and stakeholders seeking to develop projects in this domain must operate within international strategies, laws, regulations, and standards governing such activities (Johns 2013; Knapp 2013; Falconer et al 2023). Additionally, careful assessment is required in the context of ocean ecosystems, taking into account natural resources and the diverse range of human activities occurring within these marine spaces (Lovatelli et al 2013; Gentry et al 2016).

The Multiple Use of Marine Areas. To address the challenges associated with relocating aquaculture to offshore areas, an effective approach is the integrated operation of activities from multiple sectors (EU 2014; Papandroulakis et al 2017). For example, from the perspective of potential benefits, there is particular interest in establishing offshore systems that combine aquaculture with energy production within the same oceanic area (Holm et al 2017; Kite-Powell 2017).

The development of a modular, multifunctional system enables cross-border collaboration and the integration of activities across multiple sectors, while also facilitating access to remote offshore areas. A notable example is the TROPOS project, which involved several countries in the design of multifunctional modular floating platforms for deployment in deep waters of the Mediterranean and subtropical regions (Quevedo 2012, 2013). The project incorporated functions from four distinct sectors and engaged specialists from various disciplines, ultimately generating insights and recommendations for conceptual platform designs (Papandroulakis et al 2017).

The Development of Offshore Aquaculture: International Examples and the Case of Romania. Interest in the expansion of offshore aquaculture is particularly evident in countries such as Norway, China, Korea, and Singapore, which are actively investing in and advancing innovations in this sector (Wang et al 2022). Conversely, the high costs and inherent risks associated with offshore operations have led other countries to focus primarily on experimental models and pilot-scale projects (Naylor et al 2021).

European aquaculture makes a significant contribution to global fish production, and in recent years, countries within the European Union, along with Norway and Iceland,

have experienced steady growth in this sector (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Aquaculture_statistics#EU_Aquaculture). Within the European Union, fisheries and ocean management are supported not only through the Common Fisheries Policy, but also by a range of initiatives focused on aquaculture, the blue economy, and international ocean governance (Cappell et al 2024). The sector is further reinforced through substantial allocations of Community funds (https://oceans-and-fisheries.ec.europa.eu/policy/common-fisheries-policy-cfp_en).

The development of mariculture in Romania was previously hindered by an unclear regulatory framework and restrictive measures imposed by authorities, while offshore aquaculture was unfeasible due to difficulties in obtaining concessions for marine waters. Since 2021, however, the establishment of a legislative framework for marine water concessions has enabled the cultivation of fish and other aquatic organisms in floating net cages in the Black Sea (Niță & Nenciu 2023). The development and optimization of aquaculture in Romania align with the strategic priorities of the European Union. The sector's potential is supported by both natural and artificial water bodies, as well as the coastal and maritime areas of the Black Sea. Moreover, fisheries and aquaculture are identified as priority sectors within Romania's National Strategy for Sustainable Development (<https://ampeste.ro/pap-2021-2027/programare-2021-2027/proiect-de-program-2021-2027.html>; <https://www.edu.ro/sites/default/files/Strategia-nationala-pentru-dezvoltarea-durabila-a-Rom%C3%A2niei-2030.pdf>).

Conclusions. To meet the increasing global demand for aquatic products, offshore aquaculture offers a modern and sustainable alternative. This approach provides several benefits, notably the reduction of environmental pressures associated with intensive aquaculture in coastal areas and the minimization of competition with other economic activities. The implementation and expansion of aquaculture in exposed oceanic areas, however, necessitate careful consideration of specific political, economic, technical, and regulatory challenges. The costs associated with authorizing, designing, constructing, and operating offshore aquaculture systems can be mitigated through the multifunctional use of marine areas. One proposed and tested approach in certain regions is the integration of aquaculture with energy production. Addressing administrative and regulatory challenges is essential for the advancement of mariculture in Romania. By fostering collaboration among authorities, investors, producers, and research institutions, new projects can be initiated, and innovative solutions can be developed to support the implementation of aquaculture in the Black Sea.

Conflict of Interest. The authors declare that there is no conflict of interest.

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