Marine Pollution Bulletin 227 (2026) 119432

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Review

Technologies for marine biodiversity monitoring and mapping: A systematic review

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ARTICLE INFO

Keywords:
Habitat mapping and monitoring
Marine environment
Marine robotics
Underwater technologies
Interdisciplinary marine research

ABSTRACT

In recent years, major technological advances have significantly improved our ability to assess the distribution and health status of marine habitats and their associated biodiversity. Yet, comprehensive overviews of how these innovations are being applied across public and private sectors remain scarce. One reason for this gap is partly due to still scarce interdisciplinary research and to the rapid pace of technological evolution, which often renders tools quickly obsolete, making it difficult for the scientific community to stay up to date. Also, despite their enormous potential, the high costs of advanced technologies still limit their accessibility and widespread use in marine monitoring. This review addresses these challenges by providing a comprehensive overview of the methodologies currently used to monitor and map marine biodiversity across diverse marine ecosystems, with a focus on technological developments from the last decade (2014–2024). By synthesizing approaches spanning marine robotics, remote sensing, and automated sensing systems, the review highlights both the expanding observational capabilities enabled by these tools and the limitations that hinder their effective operational uptake. By adopting an integrated and application-oriented perspective, this work aims to foster and pave the way for collaboration and knowledge exchange across disciplines and sectors, especially between ecologists, engineers, and stakeholders from private and public sectors, as well as to support the development of accessible, comparable, and actionable technological pathways for marine biodiversity monitoring and conservation.

Contents

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https://doi.org/10.1016/j.marpolbul.2026.119432
Received 4 December 2025; Received in revised form 21 January 2026; Accepted 12 February 2026
Available online 24 February 2026

1. Introduction

In the current era of escalating environmental challenges, growing anthropogenic pressures, and rapid biodiversity change, the demand for accurate, timely, and spatially explicit data has never been more urgent. The ability to monitor biodiversity effectively is fundamental to understanding, mitigating, and ultimately reversing these impacts. This calls for a critical reflection on the state of available technologies: what tools are currently accessible, how well they perform across diverse ecological contexts, and where major gaps or inefficiencies remain. Yet, comprehensive, decision-ready guidelines or trends for selecting tools tailored to specific biological targets remain scarce. At the same time, there is a tendency to favor novel technologies without adequate evaluation of reliability or contextual suitability (Bainbridge et al., 2011).

Traditionally, monitoring of the ocean floor and water column has been more focused on physio-chemical variables, with limited focus on biodiversity, involving the deployment of underwater sensors for mission-specific data collection, followed by retrieval and laboratory analysis. This method is time-consuming, labor-intensive, and requires skilled personnel (Cardia et al., 2023; Akyildiz et al., 2005). Furthermore, there is no real-time situational awareness, no early warnings, and no way to remotely reconfigure instruments as environmental conditions shift. This inability to remotely operate on the instrument could furthermore lead to failures and misconfigurations being undetected until recovery (Akyildiz et al., 2005). Robotics and intelligent sensing have the potential to reshape marine biodiversity monitoring by cutting mission effort and associated risk while enhancing data collection and management (Zereik et al., 2018).

Despite the advantages, the core challenge remains to reduce human intervention, cut the power and bandwidth needed for data transmission, and scale processing to assess and forecast marine biodiversity status across broad spatial and temporal domains (Agarwala, 2020). To achieve this, researchers have pivoted toward engineering-led solutions (Wanderlingh et al., 2025), including remote sensing, passive acoustics, engineering platforms for automated environmental DNA (eDNA) sampling and archiving, marine robotics, and smart networked systems such as the Internet of Underwater Things (IoUT) (Domingo, 2012) often enhanced by Artificial Intelligence (AI). These approaches minimize on-site human involvement, enable event-driven or edge processing, improve data throughput, and often lower time and cost relative to traditional campaigns, while expanding what can be monitored. Significant challenges persist in harmonizing monitoring efforts, with the lack of standardized data and interoperability across programs. But, as monitoring frameworks have multiplied, different interpretations of the variables to observe, or "essential variables", have emerged, creating confusion and slowing progress toward a unified, global system (Miloslavich et al., 2018). To address this, the scientific community has defined standardized variables serving as reliable indicators of marine biodiversity and ecosystem health. Miloslavich et al. (2018) applied the Driver-Pressure-State-Impact-Response (DPSIR) framework to define a set of biological and ecological Essential Ocean Variables (EOVs), aiming to guide biodiversity monitoring at local and global scales. Embedded within the multidisciplinary Global Ocean Observing System (GOOS), EOVs balance scientific rigor, social relevance, and technological feasibility, and align with policy targets such as the Convention on Biological Diversity (CBD) - Aichi Targets and the United Nations Sustainable Development Goals (UN SDGs) (Miloslavich et al., 2018). The observed variables range from "phytoplankton biomass and diversity" to "seagrass and macroalgal cover and composition", each requiring fit-for-purpose tools and methodologies at appropriate spatial and temporal scales. This is crucial, as decisions regarding methodologies, instrumentation, and sampling frequency are often dictated by financial constraints rather than well-stated hypotheses and rigorous experimental designs on ecological issues. Consequently, monitoring strategies may not always be aligned with the biological questions they aim to address. Recognizing these challenges, several environmental laws and directives have increasingly emphasized the strategic role of technology in supporting effective monitoring and conservation efforts. In the European context, key legal frameworks such as the Water Framework Directive (Directive 2008/32/EC) (European Parliament and European Council, 2000), the Habitats Directive (Council Directive 92/43/EEC) (Council of the European Communities, 1992), and the Marine Strategy Framework Directive (Directive 2008/56/EC) (European Parliament and Council, 2008), require Member States to monitor the ecological status of both freshwater and marine ecosystems, to promote the conservation as well as the sustainable management of their resources (Hemery et al., 2022). Notably, the Marine Strategy Framework Directive (MSFD) underscores technology as a cornerstone for biodiversity conservation, establishing a common basis for monitoring marine ecosystems. By orienting policy toward Good Environmental Status (GES) of European seas, the MSFD positions technology as a key enabler of harmonized, effective environmental governance. Beyond Europe, international legal instruments increasingly cast technology as essential to biodiversity monitoring and conservation. The Convention on Biological Diversity (CBD) was an early promoter, foregrounding technology's role in conservation policy (UN, 1992). Subsequent frameworks reinforced this stance:

- Marine Biological Diversity of Areas Beyond National Jurisdiction (BBNJ) Agreement (2023) - safeguards biodiversity in areas beyond national jurisdiction, with provisions for advanced technologies, including robotic monitoring and technology-enabled environmental impact assessment, to support sustainable management (United Nations, 2023).
- UN 2030 Agenda for Sustainable Development (SDGs) - positions innovation as a cross-cutting enabler; SDG 14 ("Life Below Water") explicitly targets the conservation and sustainable use of the ocean, including through innovative technologies (Armstrong, 2020).
- Nature Restoration Regulation - sets restoration targets (20% of terrestrial and marine ecosystems by 2030; all degraded ecosystems by 2050) and promotes remote sensing, AI, drones, and marine robotics to achieve them (European Union, 2024).

By building on recent advances while foregrounding persistent barriers, such as cost, scalability, and interoperability, this review identifies fit for purpose, cost-effective technologies across diverse marine biodiversity monitoring contexts and outlines a strategic path forward for marine biodiversity monitoring. The purpose of this review is to pave the way for a coordinated, cross-sector approach that leverages engineering innovation, artificial intelligence, and open platforms to integrate novel tools into routine monitoring and to support evidence-based conservation and ecosystem resilience at a global scale. Specifically, the objectives are:

- Evaluate current technologies for effective marine biodiversity monitoring, with attention to habitat-specific applications and operational constraints.
- Identify gaps in the availability, accessibility, and affordability of monitoring solutions, including barriers to interoperability.
- Propose actionable pathways, combining cutting-edge engineering and AI capabilities, to enhance future monitoring, from data acquisition to analytics and decision support.

2. Methodology

This review adopts the methodology originally proposed by Chalmers and Altman (1995), refined by the Joanna Briggs Institute (JBI) as detailed in Aromataris and Pearson (2014), further updated in Aromataris and Munn (2020). The approach aligns with the PRISMA 2020 statement (Page et al., 2021) and Covidence (Couban, 2016) was used as a tool for systematic review.

2.1. Inclusion/exclusion criteria

The central question driving this review is: What is the current state of public and private technology for marine biodiversity monitoring? This inquiry is further refined into the following sub-questions:

1. What is the current status and application of technologies for monitoring marine habitats, and which are the most commonly used for each of them?
2. What are the technological limitations and the existing knowledge gaps in these applications?
3. To what extent can private entities contribute to the development of innovative monitoring tools?
4. How advanced is the use and development of artificial intelligence in marine biodiversity studies?
5. Can innovative, such as the Internet of Underwater Things and AI, and cost-effective solutions enhance remote marine biodiversity monitoring?

This systematic review includes peer-reviewed literature (e.g., research articles, reviews, book chapters, letters, editorials, books, and data articles) obtained from ISI (International Scientific Indexing) journal databases.

Inclusion Criteria

1. Studies related to marine environments;
2. Studies published from 2014 onward (i.e., within the last 10 years);
3. Studies utilizing at least one technological device (e.g., cameras, drones) for marine biodiversity monitoring;
4. Studies that report sufficient methodological details on the instrumentation used, including device specifications, operational characteristics, or deployment modalities useful to allow replication of the experiment;
5. Studies conducted in both natural and artificial conditions;
6. All publication stages, subject areas, and source types (including peer-reviewed published papers, grey literature, non-indexed conference papers, and PhD theses to incorporate all potential sources of information);
7. Studies published in languages proficiently understood by the research team (i.e., English and Italian).

Exclusion Criteria

1. Studies not related to marine environments;
2. Studies published prior to 2014 (to account for technological obsolescence);
3. Studies that do not utilize any technological or innovative devices;
4. Studies that do not provide details about the devices used in the methodology;
5. Studies that do not monitor any biodiversity variable or EOVs;
6. Studies that do not report sufficient methodological details on the instrumentation used, including device specifications, operational characteristics, or deployment modalities useful to allow replication of the experiment;
7. Articles that are not accessible or available;
8. Review articles.

In cases where disagreements arose among reviewers during the screening or data extraction phases, these were resolved through discussion and consensus, guided by the predefined inclusion criteria and the aims of the review. When necessary, the criteria listed above were reapplied to ensure consistent interpretation and relevance.

2.2. Categorization

Given the heterogeneity in aims and outcomes of each article, we categorized specific response variables to ensure comparability. Firstly, grouping into main taxonomic groups was carried out on the basis of the indications provided by each author on the species/habitats focused on the research. Threats to marine species and habitats were not included in the search strategy but were analyzed *a posteriori* as an additional step on the final pool of selected articles, using the categories proposed by Mazaris et al. (2019) and considering only threats explicitly mentioned in each study. Finally, many of the reviewed articles did not report key technical features (such as endurance, operational range, depth, and cost), essential for describing potential and limits of the adopted technologies. To address this, each technology used for monitoring marine biodiversity was classified through additional online research. Technologies were categorized according to their primary operational role and deployment domain, rather than their full set of integrated capabilities. This functional classification approach is commonly adopted in reviews of marine monitoring and robotic systems to maintain clarity when discussing hybrid and multi-sensor platform systems (Zereik et al., 2018).

Mobile and fixed robotic platforms (e.g., AUVs, ROVs, ASVs, crawlers) were classified as ‘‘robotic systems’’ based on their function as carriers enabling autonomous or remotely operated data acquisition (Agarwala, 2020). Robotic platforms were further classified according to their level of autonomy, since a key focus of this review was to assess the impact of autonomous and robotic systems on biodiversity monitoring and assessment. The classification follows the framework proposed by Seto et al. (2012) for general autonomous systems.

Optical technologies were grouped according to their primary sensing modality (e.g., RGB, multispectral, or hyperspectral imaging) (Hemery et al., 2022). Acoustic technologies were classified based on the use of sound propagation for sensing, monitoring, or communication (e.g., hydrophones, side-scan sonar, multibeam echosounders), in line with established marine monitoring frameworks (Akyildiz et al., 2005; Heidemann et al., 2012).

In cases where a single system integrated multiple sensing modalities, classification was based on the component defining the system’s main operational function, while auxiliary sensors were considered within their respective functional categories, following a platform-centric perspective widely used in marine observing system design (Cardia et al., 2023; Zereik et al., 2018).

These classification criteria were applied consistently across all figures, tables, and textual descriptions throughout the manuscript.

Table 1
Detail of keywords search strategy.

Database 1	Web of Science
Date of search:	28/02/2024
Query:	TS = ("Marine Biodiv*" OR "Marine Environment*" OR "Marine Habitat*") AND ("Biocenotic map*" OR "Ecological monitor*" OR "EOV" OR "Essential Ocean variable*" OR "Habitat Map*" OR "Habitat monitor*" OR "Map*" OR "Marine Biodiversity Monitor*" OR "Marine Monitor*" OR "Marine strategy" OR "Monitor*" OR "Temporal variation") AND ("Acoustic* monitor*" OR "AI" OR "A.I." OR "amphibious drone*" OR "Artificial Intelligence" OR "ASC" OR "ASV" OR "autonomous surface vehicle" OR "Autonomous tech*" OR "AUV" OR "Autonomous Underwater vehicl*" OR "Bio Inspired" OR "Bio-inspired" OR "Camera" OR "Deep learning" OR "Device*" OR "Distributed systems" OR "Drone*" OR "GIS" OR "Image segmentation" OR "internet of underwater things" OR "IoUT" OR "LIDAR" OR "Machine learning" OR "Marine Technol*" OR "Multispectral" OR "Marine robot*" OR "Multibeam" OR "Multi-beam" OR "Neural network*" OR "Photogrammetry" OR "Photomosaic*" OR "Remotely operated vehicle*" OR "Robot*" OR "ROV" OR "Satellite* Monitor*" OR "Sens* Net*" OR "Side-scan sonar" OR "sidescan sonar" OR "SSS" OR "Surface*" OR "Technol*" OR "Technol* status" OR "Technol* state of art" OR "Telemetry" OR "UAV" OR "Underwater device*" OR "Underwater robot*" OR "Underwater sensor*" OR "Underwater technol*" OR "Unmanned" OR "Unmanned technol*" OR "Unmanned vehicle*" OR "Videogrammetry" OR "Water Sampl*")
Results:	385 documents
Database 2	**Scopus**
Date of search:	28/02/2024
Query:	TITLE-ABS-KEY("Marine Biodiv*" OR "Marine Environment*" OR "Marine Habitat*") AND ("Marine Biodiversity Monitor*" OR "Ecological monitor*" OR "EOVs" OR "Essential Ocean variable*" OR "Habitat Map*" OR "Habitat monitor*" OR "Map*" OR "Marine Monitor*" OR "Marine strategy" OR "Monitor*" OR "Temporal variation" OR "Biocenotic map*") AND ("Acoustic* monitor*" OR "AI" OR "A.I." OR "amphibious drone*" OR "Artificial Intelligence" OR "ASC" OR "ASV" OR "autonomous surface vehicle" OR "Autonomous tech*" OR "AUV" OR "Autonomous Underwater vehicl*" OR "Bio Inspired" OR "Bio-inspired" OR "Camera" OR "Deep learning" OR "Device*" OR "Distributed systems" OR "Drone*" OR "GIS" OR "Image segmentation" OR "internet of underwater things" OR "IoUT" OR "LIDAR" OR "Machine learning" OR "Marine Technol*" OR "Multispectral" OR "Marine robot*" OR "Multibeam" OR "Multi-beam" OR "Neural network*" OR "Photogrammetry" OR "Photomosaic*" OR "Remotely operated vehicle*" OR "Robot*" OR "ROV" OR "Satellite* Monitor*" OR "Sens* Net*" OR "Side-scan sonar" OR "sidescan sonar" OR "SSS" OR "Surface*" OR "Technol*" OR "Technol* status" OR "Technol* state of art" OR "Telemetry" OR "UAV" OR "Underwater device*" OR "Underwater robot*" OR "Underwater sensor*" OR "Underwater technol*" OR "Unmanned" OR "Unmanned technol*" OR "Unmanned vehicle*" OR "Videogrammetry" OR "Water Sampl*")
Results:	443 documents
Database 3	**Google Scholar**
Date of search:	28/02/2024
Query:	"Marine Robotics for Biodiversity Monitoring"
Results:	8000+ results (only the first 200 were included)

Table 2
Summary of the main topics identified during the review of the 167 articles included in this study. The right column reports the percentage of articles addressing each topic. Specifically: 1- articles explicitly referring to climate change; 2- articles reporting monitoring efforts lasting more than two years (threshold selected to distinguish multi-year initiatives, given that most projects last approximately two years); 3- articles reporting potential threats to marine biodiversity; 4- articles mentioning the use of AI for data analysis, such as machine learning. Percentages are calculated relative to the total number of reviewed articles (n = 167).

Topics of interest	Articles expressed as %
(1) Climate change	10.8%
(2) Long term monitoring	15.5%
(3) Threat on marine biodiversity	11.4%
(4) Use of AI	56.9%

2.3. Search strategy and source of information

The search strategy for this review involved identifying key terms from articles related to the topic of the review itself within online scientific databases. The keywords used for this research are listed in Table 1.

Bibliographic research was conducted on three main databases: Scopus, Web of Science, and Google Scholar. All documents retrieved from Scopus and Web of Science were considered eligible for inclusion in the review. Unlike Scopus and Web of Science, Google Scholar does not support the use of complex Boolean search strings, which makes it impractical to replicate the same keyword combinations reported in Table 1. Therefore, a simplified query was used. Consistent with common practice and methodological guidance (e.g. Haddaway et al. (2015)), only the first 200 results ranked by relevance were screened, as relevance markedly decreases beyond this threshold. All retrieved records were subsequently imported into Covidence, where duplicates were automatically identified and removed, followed by a manual check.

2.4. Study selection

The review began with 1028 articles identified as eligible based on the keywords listed in Table 1. Covidence software was used to streamline the review process, including duplicate removal (n = 342), which was conducted both manually and automatically.

Fig. 1 illustrates the complete review process. The first step involved the identification and removal of duplicate records: out of the initial 1028 records, 342 duplicates were eliminated. In the first screening phase, the remaining 686 articles were screened based on their titles and abstracts, leading to the exclusion of 349 articles that did not meet the inclusion criteria. During the second screening phase, the 337 remaining articles were assessed for eligibility through full-text analysis, resulting in the further exclusion of 170 articles according to the inclusion and exclusion criteria. In the final phase, the remaining 167 articles were included for data extraction.

3. Results

3.1. Temporal trends in research publications

The number of studies using technologies to monitor marine biodiversity shows a general increase in publications over the last 10 years, with a peak in 2021 (Fig. 2).

In terms of general topics, the analysis of the literature showed that a relevant number of studies are employing artificial intelligence to support their research. Threats affecting marine biodiversity are rarely considered, and long-term monitoring activities (>2 years) using technologies are poorly represented. In addition, studies explicitly addressing climate change monitoring remain very limited, revealing a lack of substantial effort to investigate this phenomenon through technological approaches (Table 2).

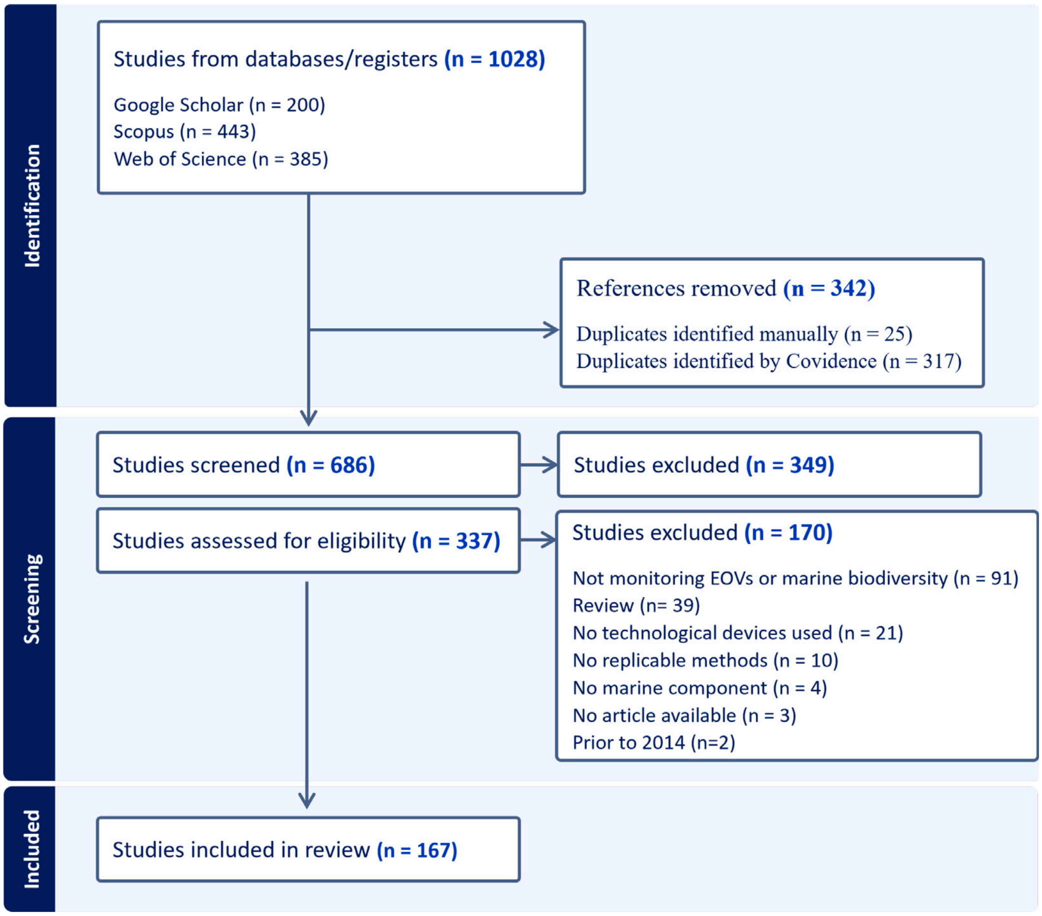

Fig. 1. Results of the covidence article review process. From 1028 articles based on Scopus, Google Scholar and Web of Science research, to the final 167 articles included in the final review.

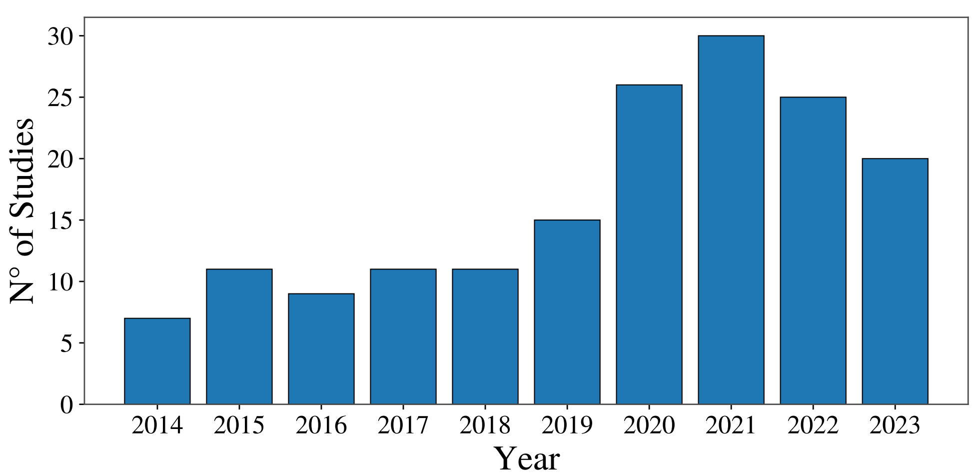

Fig. 2. Articles published per year, from 2014 to 2024. Since 2024 includes only two studies, they were excluded from the analysis but remain included in all subsequent results.

3.2. Study location

Among the 167 articles reviewed, 196 different study locations were analyzed, including 42 Marine Protected Areas (MPAs) and 154 non-MPAs. The spatial distribution of the study locations shows that Europe is the most representative continent for using technologies for marine biodiversity monitoring. South East Asia and America's West Coast are also well represented. There are also isolated locations in the middle of the Pacific Ocean, Atlantic Ocean, and Antarctic Ocean, showing that studies are well spread worldwide. Fig. 3 highlights all study locations, with blue dots representing studies conducted within MPAs and red dots are the ones which are carried out outside protected areas.

3.3. Taxa and EOVs monitored

Information was retrieved for 14 taxonomic groups, most of which were associated with benthic communities (Fig. 4).

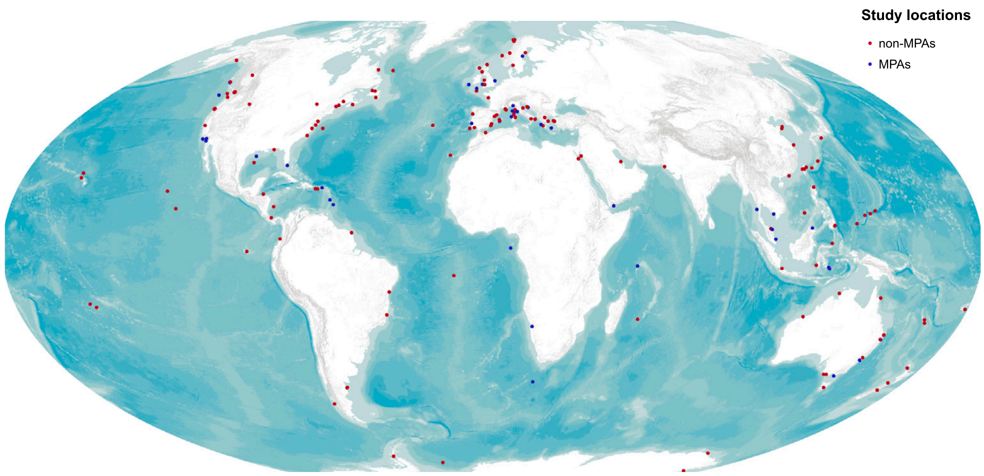

Fig. 3. Spatial distribution of the studies considered in this review. Studies conducted outside protected zones are represented by red dots, whereas those carried out within MPAs are in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

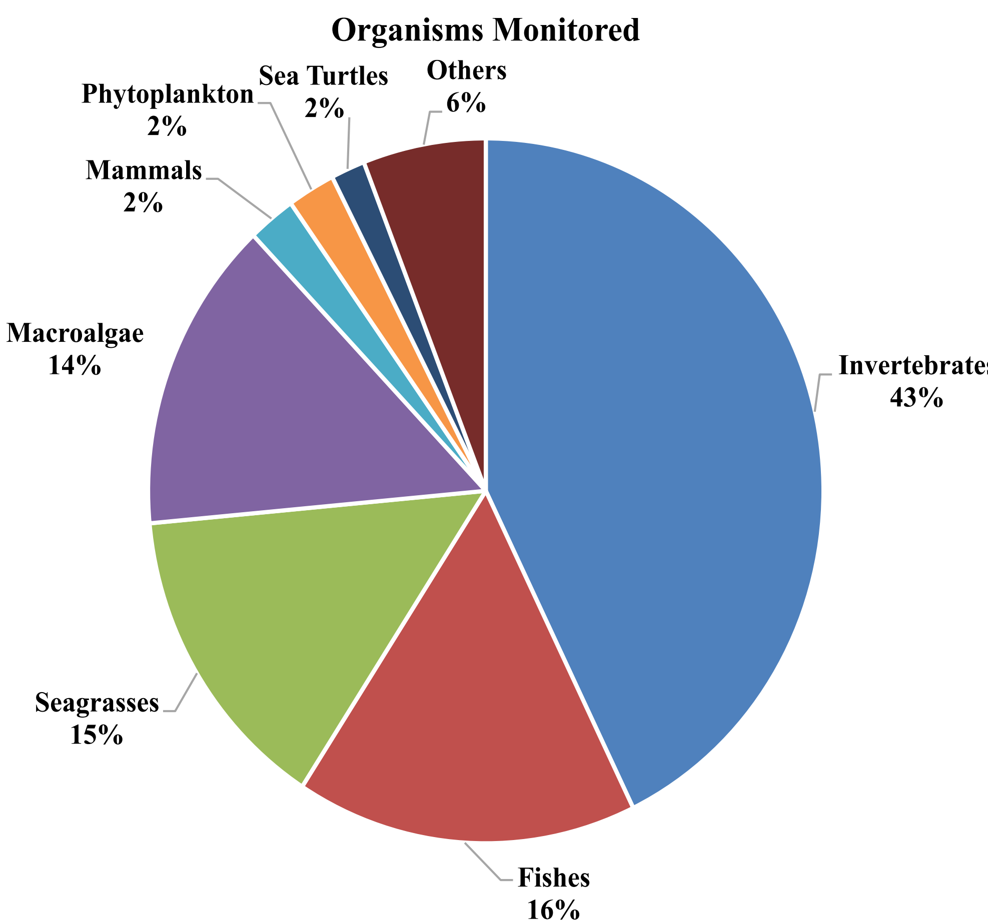

Fig. 4. Monitored marine organisms in reviewed articles divided by taxonomic groups. Kelp are included in the Macroalgae group. The category "Others" was harmonized at a consistent taxonomic level and includes: Hydrozoans, Tunicates, Birds, Cyanobacteria, lichen-forming fungi, Rhodolith-forming taxa, mangroves and freshwater plants.

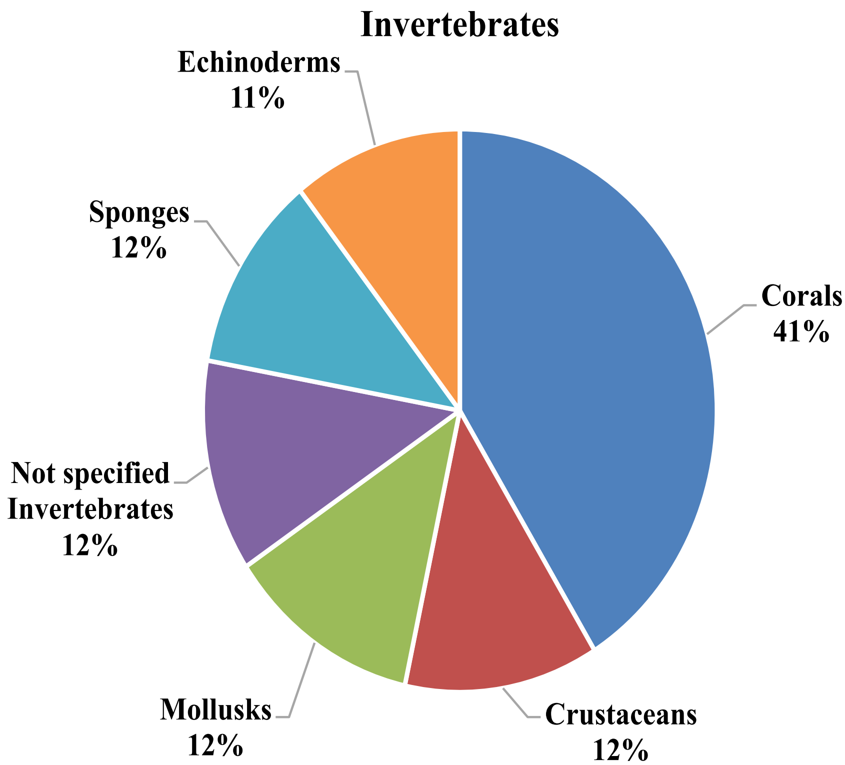

Fig. 5. Invertebrates subdivided into specific taxa for improved visualization.

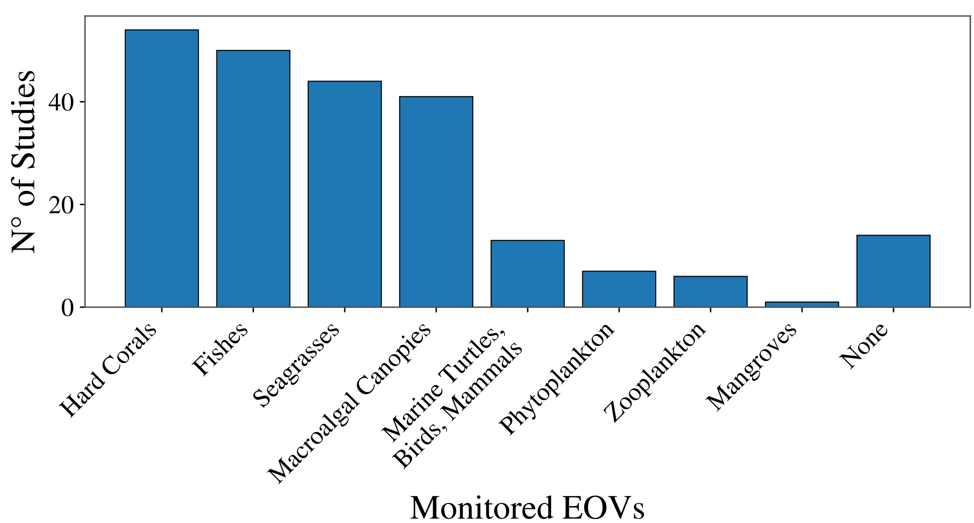

Fig. 6. Essential Ocean Variables (EOVs) monitored in the reviewed studies.

Invertebrates are the most represented group, followed by fishes and seagrasses. To provide a more detailed overview, invertebrates were further classified into subgroups (Fig. 5), with corals being the most represented subgroup, accounting for nearly half of the total invertebrate records, followed by crustaceans and mollusks.

Essential Ocean Variables (EOVs) (Miloslavich et al., 2018) were extracted from the pool of articles, with Coral cover, fish abundance, seagrasses and macroalgal cover being the most represented by far, followed by marine mammals and turtles, and phyto/zooplankton (Fig. 6).

3.4. Environmental variables

The environmental variables most frequently monitored across the reviewed studies included water temperature, salinity, dissolved oxygen, turbidity, nutrient concentrations, pH, and dissolved organic carbon. Among these, water temperature (expressed in °C) is the most measured variable (Fig. 7).

3.5. Threats

Threats were also categorized based on what was found in selected articles and summarized in Fig. 8. Unspecified anthropogenic pressures were the most frequently reported, followed by fishing (including trawling) and invasive species. Bleaching events and floating marine litter were less commonly investigated.

3.6. State-of-the-art technologies and habitats monitored

The review examined four operational domains, defined by the

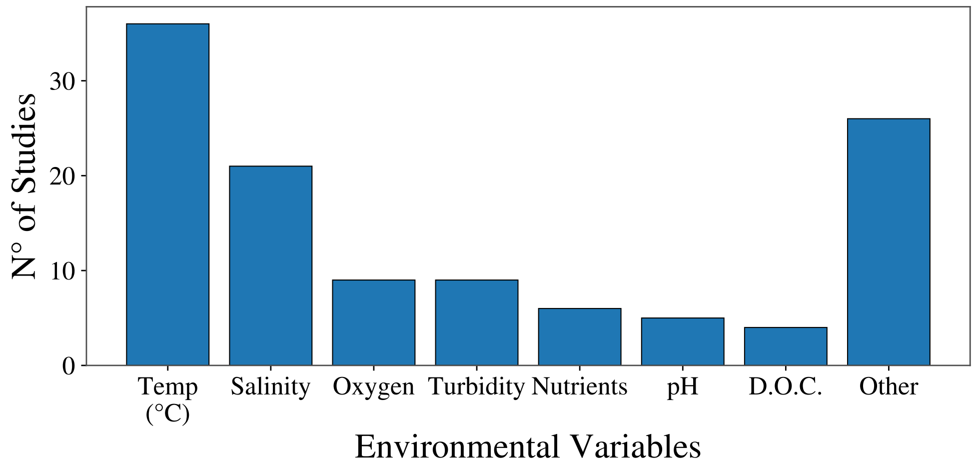

Fig. 7. Most common observed environmental variables in reviewed articles.

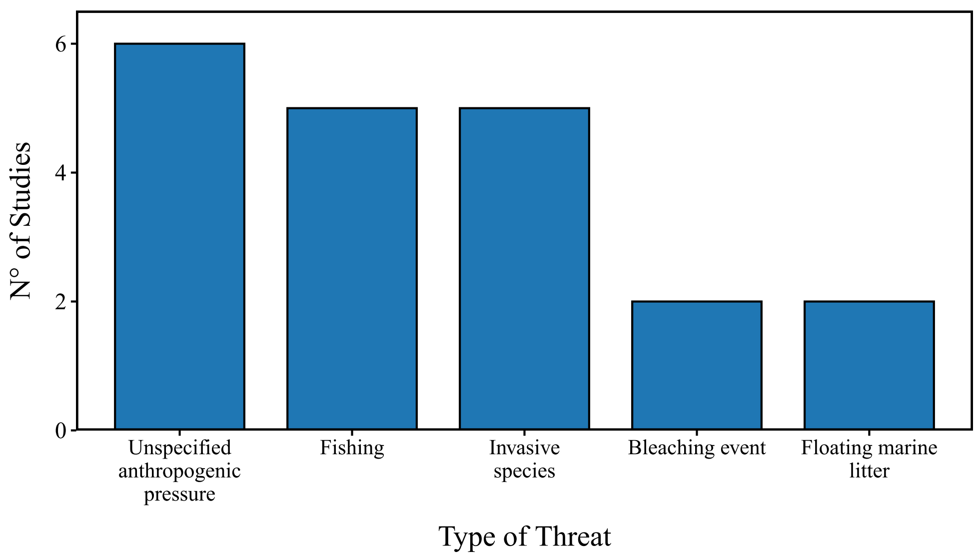

Fig. 8. Types of threats on biodiversity considered in the analyzed studies. The categories reported in this graph are based on those proposed in Mazaris et al. (2019) and were rephrased to better reflect the evidence emerging from the reviewed articles.

environment and platform of data acquisition, where technologies are used for marine biodiversity monitoring and mapping: underwater, water surface, airborne, and spaceborne. Fig. 9 shows the distribution of technologies across these domains.

Across the reviewed operational domains, robotics and intelligent systems play a fundamental role in marine biodiversity monitoring and assessment by drastically reducing the effort required for data collection (Zereik et al., 2018). The cutting-edge state-of-the-art technologies currently employed (Antonelli et al., 2021; Aguzzi et al., 2024) include:

- Remotely Operated Vehicle (ROV) — Unmanned underwater robots controlled remotely by an operator aboard a surface vessel. These vehicles are tethered to the ship via cables that transmit control commands to the unit while relaying video and image feeds back to the operator in real-time. ROVs can be equipped with robotic manipulators, cutting arms, water samplers, and instruments for the physical and chemical analysis of the aquatic environment. Their size can range from compact models to those as large as a small truck, requiring a winch system for deployment and retrieval from the water.
- Cabled Observatories — Unmanned, seafloor-based oceanographic research platforms connected to land via cables that provide power and real-time data transmission. These observatories can be equipped with a wide range of scientific instruments capable of collecting various types of data from both the seafloor and the surrounding water column. However, their operation is subject to several limitations, including biofouling, connectivity issues, potential leakages, and challenges related to proper installation and maintenance.
- Baited Remote Underwater Video (BRUV) — An underwater video system used in marine biology to attract fish into the field of view of a remotely operated camera. This system consists of a baited canister lowered to the seafloor either from a surface vessel or by a remotely operated vehicle. BRUV is a non-invasive and non-extractive technique, particularly effective in attracting scavengers and predatory species, allowing for passive observation without disturbing the natural behavior of marine organisms.
- Towed Sledge — A specialized sled designed to be towed by a vessel while gliding over soft, non-rocky seabeds. Its primary function is to collect organisms present in the uppermost layers of sediment, providing valuable biological and ecological data for marine research.
- Benthic Chambers — Autonomous observational platforms placed on the seabed or in benthic zones to monitor physical, chemical, and biological activity. These chambers can be deployed for periods ranging from a few days to several years, depending on

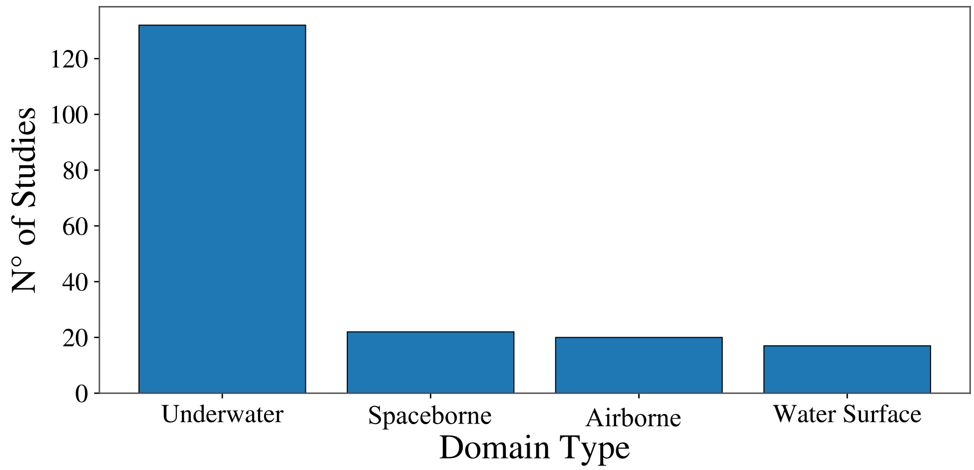

Fig. 9. Distribution of the reviewed studies according to the domain types investigated. Technologies are classified according to their primary operational role and deployment domain, as described in Section 2.2.

research needs. Equipped with a variety of instruments for underwater measurements, their design and configuration are tailored to specific scientific objectives, allowing for in-depth analysis of benthic ecosystem processes.

- Satellites — Satellites play a crucial role in remote sensing applications, serving multiple purposes in marine research and environmental monitoring. By equipping marine species such as whales, sharks, and turtles with satellite trackers, researchers can monitor their movements, identify migratory patterns, and analyze oceanic features such as currents, fronts, and eddies. Additionally, satellite technology enables the detection of phytoplankton and plant pigments in the ocean, providing valuable insights into marine ecosystem productivity. This information aids in estimating fish population sizes, offering fishery experts a deeper understanding of the health and economic value of commercial fisheries and protected marine resources. Moreover, as "eyes in the sky", satellites can detect marine debris and oil spills, helping to mitigate environmental damage and support conservation efforts.
- Unmanned Aerial Vehicles (UAVs) — Aerial drones capable of flying either autonomously or under remote control by an operator. The use of UAVs has significantly enhanced the ability to monitor marine environments from higher altitudes, enabling researchers to conduct rapid mapping, large-scale surveillance of aquatic areas, and observations of marine species. By equipping UAVs with specialized instruments beyond high-definition cameras – such as spectral sensors for detecting specific types of marine flora – it is possible to conduct more detailed environmental analyses.
- Amphibious Unmanned Aerial Vehicles (Amphibious UAVs) – Hybrid aerial drones capable of both flying and landing on the water surface. In addition to performing standard UAV tasks, these vehicles can also conduct underwater measurements of the physical, chemical, and biological properties of the marine environment. Their dual-operation capability enhances environmental monitoring by enabling seamless transitions between aerial and aquatic data collection (Miozza et al., 2023).
- Autonomous Surface Vehicle (ASV) — Unmanned surface vehicles operating on the water surface and recording oceanographic data and environmental variables. ASVs are typically larger than Autonomous Underwater Vehicles (AUVs), allowing them to carry heavier payloads and larger battery capacity. Due to their surface operation, ASVs can harness renewable energy sources such as solar or wind power to extend their operational endurance. However, their use presents unique challenges, particularly in inshore environments or congested waters, where navigation requires careful control and risk management.
- Buoys — Technological platforms designed to study oceanic processes over extended periods, which would be impractical to measure from research vessels that can only provide short-term recordings of marine conditions. Equipped with a range of sophisticated instruments, buoys can measure parameters such as water velocity, salinity, and temperature across different locations and time scales. Additionally, they enable the study of ocean-atmosphere interactions, which are challenging to monitor via satellites. Buoys can either be moored in a fixed position or left to drift with ocean currents, offering flexible data collection capabilities for long-term marine monitoring.

Regardless of the operational domain, the adaptability of technologies to different habitats was also analyzed to assess their versatility. The results of this analysis are further detailed in Fig. 10, which illustrates the specific habitats where each technology has been applied. This analysis can assist researchers in selecting the most suitable tools for their studies, while also providing valuable insights for stakeholders and engineers in the development of new and more specialized monitoring technologies. Underwater cameras (n = 123) and RGB cameras (n = 95) were the most frequently employed technologies in the reviewed studies. The data show these technologies were predominantly applied to monitor coral reefs (n = 92), seagrass meadows (n = 70), and pelagic environments (n = 70). Underwater cameras differ from standard RGB cameras in their intended application: while RGB cameras are designed for general use and can be used in hand-held (i.e. action cameras or reflex cameras), underwater cameras are specifically engineered to operate in marine environments. Remotely Operated Vehicles (ROVs) represent the third most frequently employed technology, particularly in deep-sea research. When considering habitat types, excluding pelagic and "unspecified benthic environments", coral reefs accounted for the largest proportion of studies, followed by seagrass meadows.

All technologies presented in this study are typically paired with standard monitoring tools or sensors that are commonly used for biodiversity monitoring and assessment. Fig. 11 shows the specific habitats in which a selection of these tools and sensors have been applied. Multibeam Echosounder (MBES), Conductivity-Temperature-Depth probes (CTD), Side-scan sonars, and Automated Samplers emerged as the most widely adopted tools for biodiversity monitoring and mapping.

Furthermore, Fig. 12 documents which technologies can perform real-time data analysis, a feature that can significantly influence the decision-making process when selecting the most suitable technology for a specific application.

As shown in Fig. 13, the majority of the technologies were commercially available. We also identified 15 studies that utilized open-source software and 45 that relied on proprietary software.

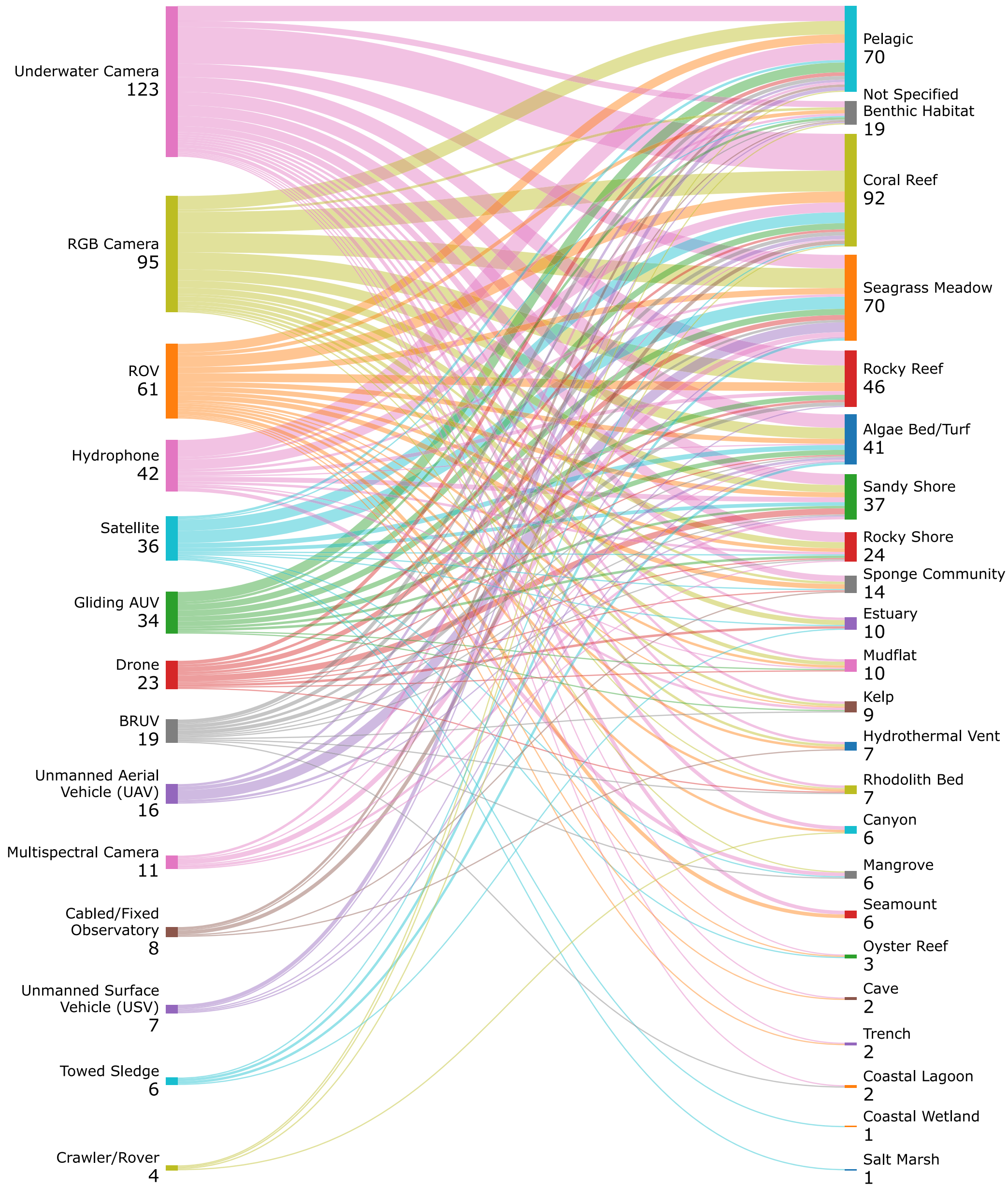

Fig. 10. Sankey diagram of common monitoring technologies and their application to marine habitats (Álvarez-Romero et al., 2018). While "RGB Camera" represents general purpose cameras used also in professional photography, Underwater Camera is used to represent tools specifically made to be used underwater or in B/W for marine purposes. "BRUV" denotes Baited Remote Underwater Video, encompassing all such systems utilized in the reviewed studies. Technologies are classified according to their primary operational role and deployment domain, as described in Section 2.2.

As a complementary investigation, we assessed the accessibility of the technologies by categorizing them into those that are readily available and those that require significant acquisition times. The results show that 80 studies employed standard, commercially available technologies that can be purchased and deployed immediately, while 84 studies relied on technologies that are not immediately available off the shelf and that may require longer and/or variable lead times before delivery, depending on the manufacturer, production schedule, or degree of customization. In 4 studies, this information was not reported. Given the growing integration of artificial intelligence (AI) across various fields, we identified studies that incorporated AI to better understand its application in biodiversity monitoring and conservation. More than half (56%) of the studies employed Machine Learning (ML) algorithms or Deep Neural Networks (DNN) (Table 2). Furthermore, the level of autonomy of each technology was classified using the framework proposed by Seto et al. (2012). The results of this classification are presented in Fig. 14.

To provide additional technical insights about the technologies considered, we classified them based on their endurance and operational range, identifying three macro-groups:

- More than one week (e.g., several weeks or months).
- Between one day and one week (more than one day but less than a week).
- One day or less (e.g., up to 24 h)

However, this information was available for 66 of 168 technologies, as the majority of articles did not provide sufficient information on the effective endurance of the systems used. For example, some technologies capable of lasting weeks were used only for daily activities, making more accurate classification difficult (Fig. 15).

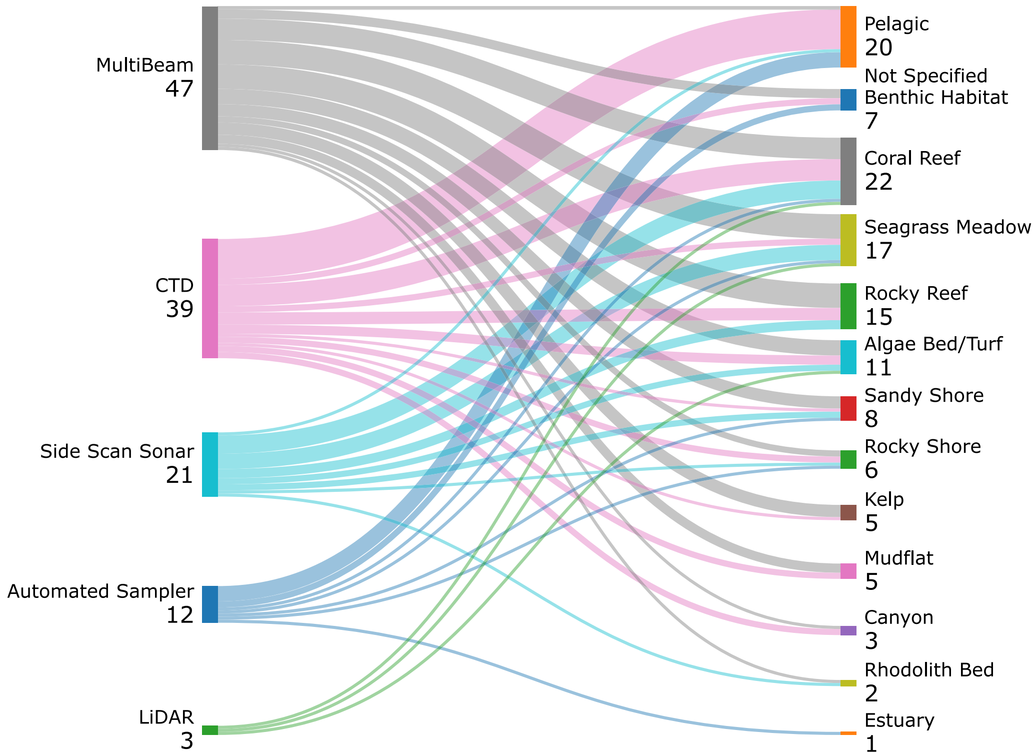

Fig. 11. Sankey diagram of common monitoring tools or sensing technologies and their application to marine habitats (Konoplin et al., 2022). Technologies are classified according to their primary operational role and deployment domain, as described in Section 2.2.

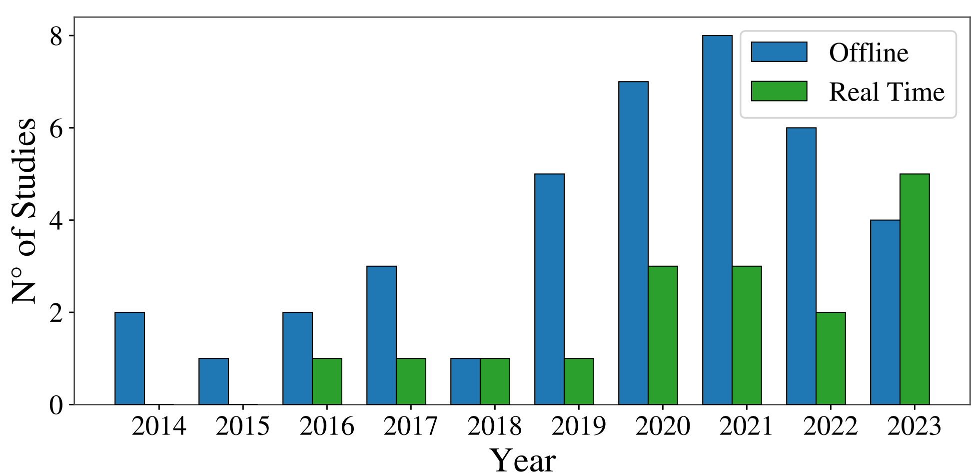

Fig. 12. Offline vs. Real time data analysis. The usage of real-time technologies and sensing methods with offline data gathering means are compared. As for temporal trends, 2024 was omitted for better representation. Technologies are classified according to their primary operational role and deployment domain, as described in Section 2.2.

From a practical perspective, technologies were also classified according to their operational range. The analysis revealed that the majority of technologies were stationary systems (94 out of 168 studies). For non-stationary technologies, operational ranges vary from meters to thousands of kilometers. We propose the classification in Fig. 16. To provide more detailed technical information, we also evaluated the underwater technologies based on their maximum depth (see Fig. 17) and the aerial technologies based on their flying height.

Aerial technologies generally matched the capabilities of modern commercially available drones, so no additional classification was necessary. Also, an in-depth analysis of the economic and commercial aspects of the technologies under consideration shows that, regarding availability to end users, nearly two-thirds (n = 100) of the studies relied on commercial solutions. In terms of software, the majority of studies used proprietary programs, while only 16 employed open-source alternatives. Quantifying the cost of each technology proved challenging due to the frequent absence of explicit cost information in the reviewed studies. However, we estimated the costs by comparing the technologies used with commercially available solutions found online. As shown in Fig. 18, the majority of cases do not exceed €1000 (88 occurrences). Estimates are based on unit prices or average values obtained from online sources. Metrics such as cost per square meter (not including operator costs, consumables and other factors as these are even harder to calculate and highly dependent on the service provider) or daily/monthly rental fees were not considered; the analysis focused solely on the purchase price of individual tools, as accurately

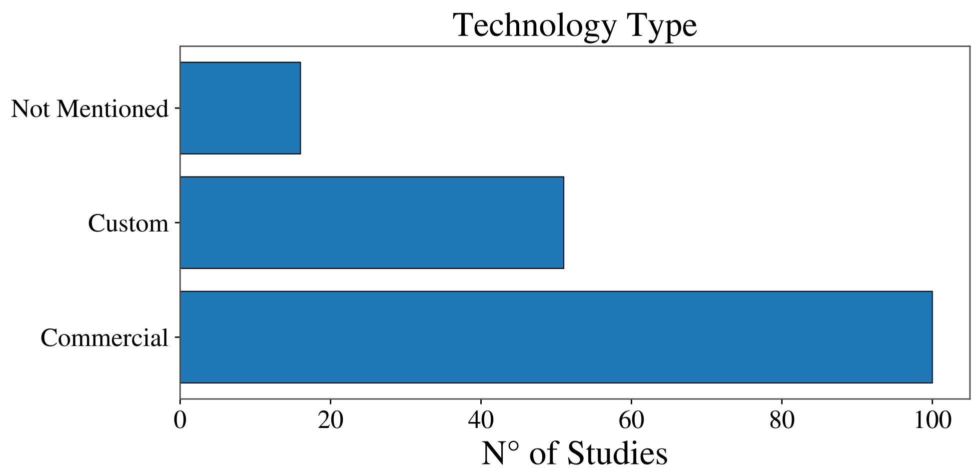

Fig. 13. The usage of commercial vs. custom technologies in reviewed articles. Commercial stands for devices that can be easily acquired via online shops or manufacturers, while Custom are all technologies that are built by the researchers themselves. Technologies are classified according to their primary operational role and deployment domain, as described in Section 2.2.

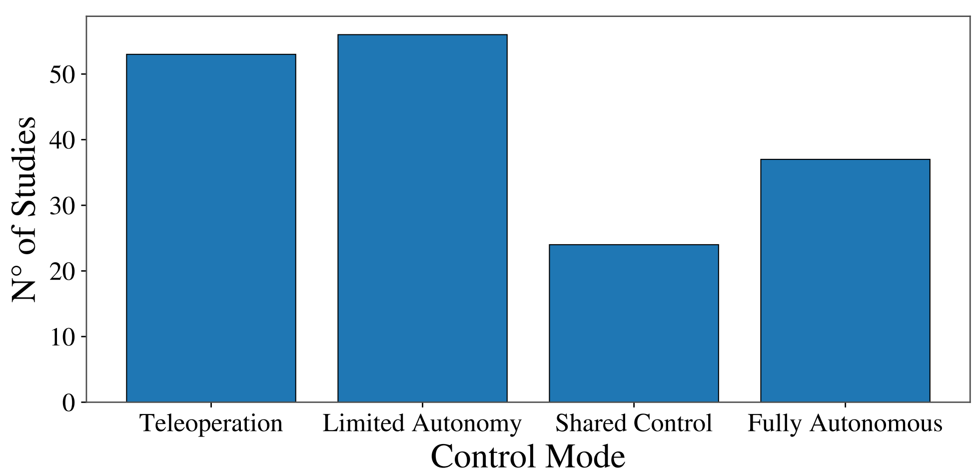

Fig. 14. The graph classifies the technologies used in the studies considered. We consider four possible categories according to Seto et al. (2012): (A) teleoperation, (B) Supervisory control with limited autonomy, (C) Shared Control, (D) Fully autonomous. Technologies are classified according to their primary operational role and deployment domain, as described in Section 2.2.

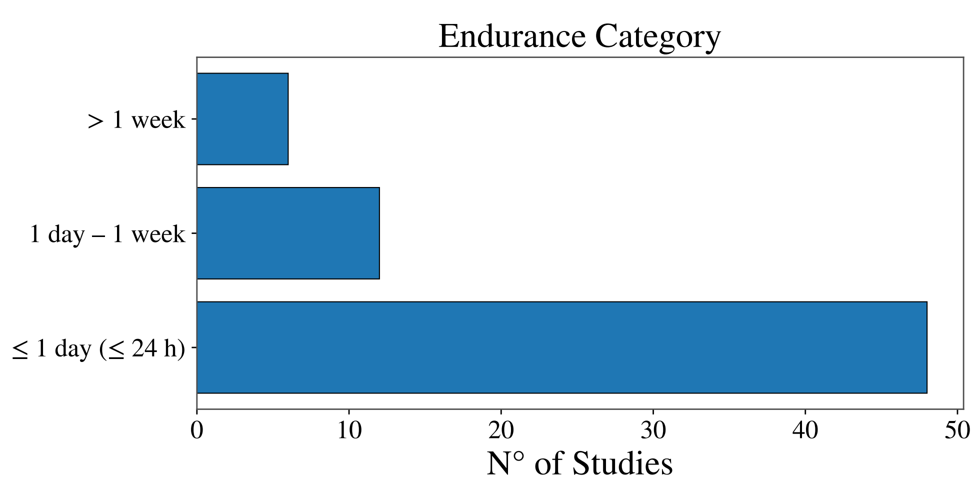

Fig. 15. Endurance levels of technologies used in the reviewed studies, based on information from manufacturers' websites and technical specifications.

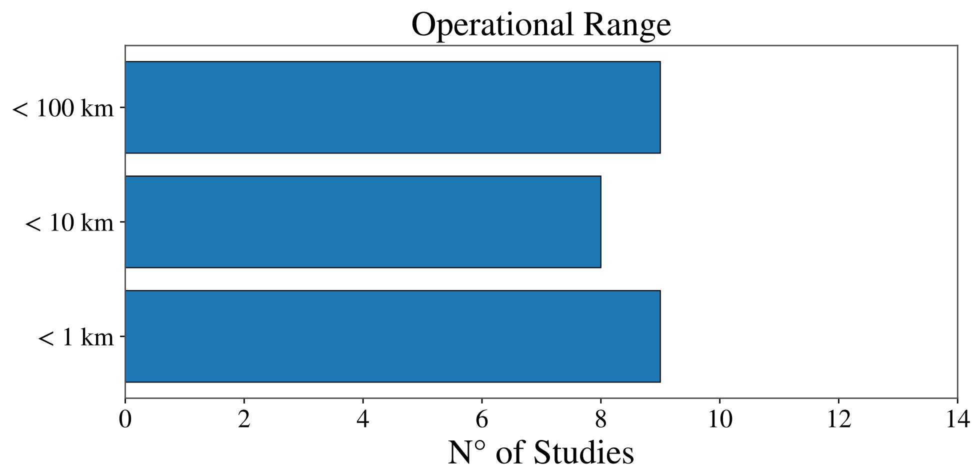

Fig. 16. Operational range of technological devices used in the reviewed studies, based on information from manufacturers' websites and technical specifications.

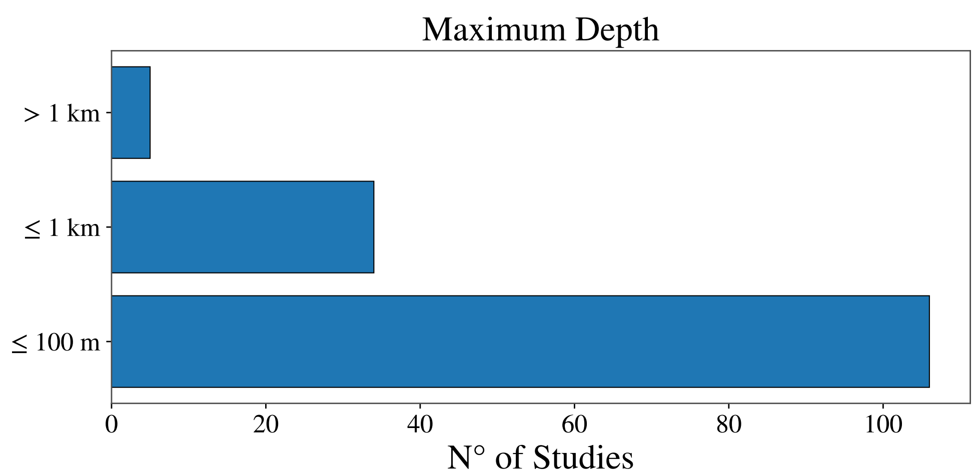

Fig. 17. Maximum depth of technological devices used in the reviewed studies, based on information from manufacturers' websites and technical specifications.

assessing a price-to-performance ratio or standardizing measures of resolution and efficiency remains challenging.

4. Discussion

4.1. Cross-analysis on technologies and habitats monitored

The analysis of the relationship between technologies and habitats reveals relevant results. As shown in Fig. 9, among the four operational domains considered in this review, underwater habitats are receiving the most attention. This trend is demonstrating the willingness to overcome technical challenges associated with operating in such a demanding setting. Moreover, the study of the underwater environment is becoming increasingly relevant for biodiversity monitoring, likely due to the increasing need for data availability and information compared to other operational domains, together with the growing economic interest involved in the exploitation of the marine environment (Jouffray et al., 2020). It is worth noticing that some underwater technologies can also be used on the surface, but not *vice versa*; consequently, some technologies listed as underwater have been used for operations at or near the surface. In this study, EOVs (Miloslavich et al., 2018) are used as an interpretative framework to link monitoring technologies with biologically and ecologically response variables, encompassing both key groups (e.g. plankton, fishes, megafauna) and habitat-forming taxa (e.g. coral reefs, seagrass meadows, macroalgae). Many of the technologies addressed directly contribute to the assessment of these variables (Fig. 6), while emerging EOVs, such as microbial diversity (GOOS Biology and Ecosystems Expert Panel, 2025b) and benthic invertebrates (GOOS Biology and Ecosystems Expert Panel, 2025a), remain constrained by current technological limitations. Importantly, differences observed among EOVs reflect not only technological preferences but also the intrinsic temporal scales required to detect ecological change, which influence the patterns observed. Not surprisingly, coral reefs, fishes, macroalgal canopies and seagrass meadows are the groups most monitored by a variety of technologies (from underwater cameras to satellites), primarily due to their feasibility, ecological relevance and visibility in public perception. However, the pelagic environment is receiving increasing attention, thus demonstrating the growing awareness of the importance of incorporating the three-dimensional nature of the ocean (Board et al., 2024). Water temperature emerges as one of the most fundamental environmental response variables, potentially providing relevant data on fluctuations in thermal regimes. Salinity represented the second most frequently recorded variable, confirming the centrality of physical oceanographic variables in studies dealing with the marine environment. This result can be explained by the relatively low cost, ease of use, and widespread availability of temperature sensors, which make temperature an accessible parameter to monitor even

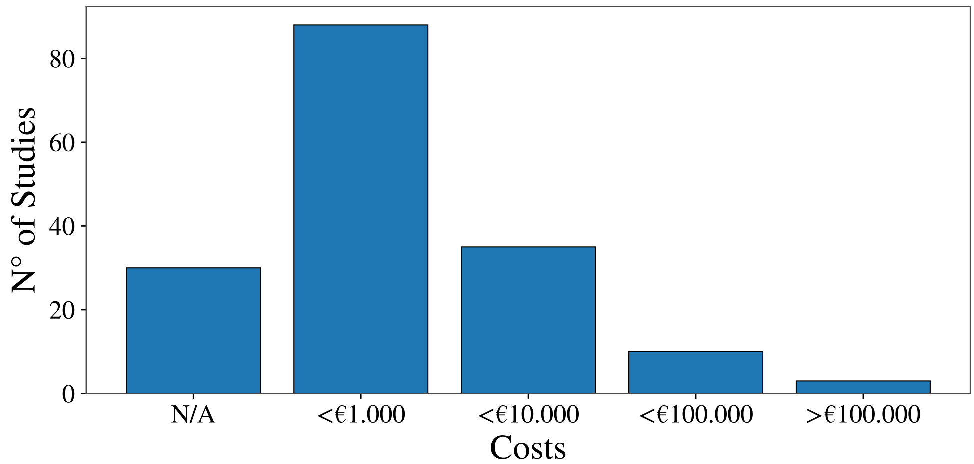

Fig. 18. Number of articles mentioning costs. We used the price stated in the reference article, where available. Online shops or the manufacturer's website was used as a reference. N/A refers to technologies for which costs information could not be retrieved online or not specified by author.

in resource-limited contexts. CTD (Conductivity-Temperature-Depth) probes are among the most widely adopted instruments in marine monitoring owing to their robustness, reliability, and accessibility to the scientific community. However, irregular distribution in time, spatial inhomogeneity, and change of instrumentation (e.g. one instrument is stored and another is subsequently deployed) are still considered sources of noise in data collection or data loss to the in situ data, possibly resulting in data overdispersion, increasing the potential of masking general trends (Rivetti et al., 2014). The analysis proceeded by evaluating the type of technologies used across habitats (see Section 3.6). Remotely Operated Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs), and drones are some of the most versatile technologies, applicable to multiple habitats. Their advantages in autonomy, spatial coverage, and resolution make them adaptable across environments, emphasizing the versatility that robotic systems provide. This versatility suggests that future research should not only continue advancing robotics for specific habitats but also explore cross-domain applications, where the same platforms can be adapted to operate effectively in different environments. Such developments could foster more integrated and cost-efficient monitoring strategies, enhancing our ability to capture biodiversity dynamics at broader scales. Building on the versatility of robotic platforms, another important trend concerns the processing capabilities of the technologies employed. While most solutions still rely on offline data analysis (Fig. 12), there is a clear movement toward real-time data processing. This trend is closely related to the rapidly increasing volume and complexity of data generated by modern monitoring platforms. High-resolution imagery, long-duration acoustic recordings, hyperspectral data, and continuous multi-parametric sensor streams can produce extremely large and heterogeneous datasets, particularly in long-term or large-scale deployments. Furthermore, gathering these data is not trivial and can be logistically challenging, especially in remote or underwater environments where bandwidth is limited and physical recovery of instruments is often required. Beyond collection, data processing remains a substantial bottleneck, as automated classification and analysis pipelines still require extensive training data, careful validation, and significant expert supervision to ensure ecological reliability. As a result, data handling and analysis can demand as much time and expertise as the deployment of the monitoring technologies themselves. Finally, the way in which these datasets are archived and disseminated is often under reported, limiting reproducibility, reuse, and integration into broader biodiversity information systems. It is worth remarking that online data analysis, when feasible, serves as a powerful instrument for real-time monitoring of habitat conditions, like cabled observatories (Heidemann et al., 2012). However, these systems face limitations in spatial coverage due to the high deployment and maintenance costs, primarily related to cabling and cable protection (Cardia et al., 2023; Cario et al., 2017). Moreover, these observatories are often installed several miles offshore, adding another layer of complexity, especially when operating in harsh sea and weather conditions (Cario et al., 2017). Similarly, the wired connection of cabled submersibles (i.e., ROVs) offers high-speed communication and continuous power to the remote end (Heidemann et al., 2012). However, when considering disadvantages in the context of marine biodiversity monitoring, tethering may disrupt delicate underwater ecosystems, causing harm to the environment in which they operate, and requiring skilled operators for their handling (Konoplin et al., 2022). Some of these issues could be mitigated by using wireless links, which offer potentially more flexible, and environmentally friendly solutions (Tretjakova et al., 2022). Among the technologies considered, Underwater Wireless Sensor Networks (UWSNs) are frequently employed to enable remote monitoring and real-time data analysis of the underwater domain through acoustic waves (Akyildiz et al., 2005). They face challenges such as limited battery life, physical deterioration due to fouling and corrosion, and reliability issues with acoustic communication, which is strongly influenced by the physicochemical properties and variability of the marine environment (Akyildiz et al., 2005; Heidemann et al., 2012; Kao et al., 2017). Despite these limitations, the use of UWSNs is gradually shifting the monitoring paradigm toward the concept of the Internet of Underwater Things (IoUT), which extends the Internet of Things framework to the underwater domain and could drastically improve marine biodiversity monitoring and mapping. In principle, IoUT nodes can be equipped with multi-parametric sensors to measure physical, chemical, and biological variables simultaneously (Akyildiz et al., 2005; Heidemann et al., 2012). They can also activate underwater devices such as cameras and hydrophones (Konoplin et al., 2022), offering a more comprehensive understanding of the processes occurring in the marine habitats while reducing repeated missions and operational costs. The IoUT architecture is flexible and easier to deploy and maintain than cabled infrastructures (Cario et al., 2017). However, it still faces challenges related to the limitations of UWSNs, including energy consumption, fouling and corrosion, lack of self-management capabilities, the reliability of acoustic communication, and the absence of standardized protocols for interoperability (Akyildiz et al., 2005; Heidemann et al., 2012; Kao et al., 2017; Cario et al., 2017; Konoplin et al., 2022)

4.2. Technological features and emerging trends

The increasing use of artificial intelligence (AI) and the adoption of intelligent systems is another relevant outcome of the review, aligning with emerging trends in big data analysis (Wanderlingh et al., 2025). As outlined in Section 3.6, AI has been applied in more than 50% of the studies considered, primarily for data processing rather than for enhancing the autonomy of robotic platforms. This distinction is reflected in the classification of monitoring systems by autonomy, shown in Fig. 14. The analysis revealed that most technologies still rely on teleoperation or supervised control with limited autonomy, although fully autonomous solutions are becoming more common. Autonomous Underwater Vehicles (AUVs), for example, can operate independently without tethers, cables, or remote control, providing flexibility and efficiency in marine monitoring (Akyildiz et al., 2005; Wanderlingh et al., 2025). Some AUVs can also surface to recharge their batteries using solar energy, enabling them to collect extensive, high-quality data and operate for long periods without frequent human intervention (Akyildiz et al., 2005; Domingo, 2012). This capability makes them particularly well suited for monitoring remote or hazardous environments (Akyildiz et al., 2005). Given these advantages, enhancing AUV autonomy through AI represents a promising future direction, as it would allow such systems to make more complex decisions in real-time, further reducing human intervention and expanding their monitoring potential. Although teleoperated and supervised systems remain predominant, fully autonomous solutions already account for about 25% of the studies reviewed. This trend is especially relevant because higher levels of autonomy can reduce deployment and maintenance costs while improving responsiveness in challenging environments (Murphy, 2004). From a technical perspective, technologies were further categorized based on weight, including both payload and total mass, operational range (both underwater and in air), and endurance. However, as payload and mass data were inconsistent and highly heterogeneous across sources, we decided not to include these variables in the review in order to provide a clearer and more coherent overview of the current state of the art. In terms of endurance, most technologies are designed for short-term monitoring, typically lasting less than 24 h. While developing long-lasting technologies is challenging, long-term monitoring (e.g., cabled observatories and benthic chambers) is crucial for understanding the temporal trends of the status of biodiversity, environmental changes, and human activities. Regarding operational range, stationary technologies proved to be prevalent, while non-stationary ones are evenly distributed across the categories proposed in Section 3.6. As depth increases, the number of available technologies decreases, highlighting a research gap in deep-sea monitoring, primarily due to the technical challenges of operating in such harsh environments.

From an economic standpoint, the results suggest an increasing prevalence of commercial solutions as described in Fig. 19. This trend highlights a growing interest in biodiversity monitoring and mapping, particularly from private companies investing in marine exploration. It also extends to proprietary software, which currently dominates the field. It is worth noticing that most studies did not report information about the software used, possibly due to privacy concerns or proprietary restrictions, or even considering it irrelevant. However, this detail is crucial for end users when designing a monitoring system, as it directly affects accessibility, flexibility, and overall cost. Furthermore, the cost analysis revealed a general lack of transparency by researchers in reporting the expenses related to the technologies they use. This gap in the literature is significant, as a clear understanding of the monitoring costs for specific habitats can greatly inform both practitioners, decision-makers, and researchers. Nevertheless, through a more in-depth examination, we were able to estimate costs and found that while many solutions are becoming increasingly affordable, a substantial number still exceed €10.000. This finding underscores the wide variability in cost-effectiveness among the tools currently available. Despite the efforts to develop affordable solutions, a gap persists between leading, well-funded research institutions and those with limited financial resources. To address this disparity, it is crucial to prioritize the development of future cost-effective solutions that balance affordability and quality. By doing so, even resource-constrained institutions could access advanced tools without compromising research standards, ultimately achieving a better price-to-quality ratio.

5. Conclusions

This systematic review offered a comprehensive and critical synthesis of current technologies used in marine biodiversity monitoring and mapping, including advances in marine robotics (e.g., AUVs, ASVs, ROVs), remote sensing, AI-powered tools, and emerging Internet of Underwater Things (IoUT) systems. Collectively, the literature demonstrates a rapid expansion of observational capacity across spatial and temporal scales, enabling increasingly data-rich assessments of marine species and ecosystems and contributing to improved knowledge of the marine environment. Beyond documenting technological progress, a major contribution of this review is the identification of persistent structural gaps that limit the practical implementation of these technologies, particularly in resource-limited institutions. A primary barrier uncovered by this analysis is the pervasive lack of standardized and transparent reporting of key technical and economic metrics within the literature, such as costs, operational endurance, sensor performance, and software architectures. This absence of consistent information limits meaningful comparisons among technologies, obstructs true cost-benefit analyses, and hinders the formulation of the actionable pathways this review sought to identify.

The impact of emerging technologies is closely linked to these structural gaps. AI-based methods, for example, can greatly improve the efficiency of data processing and support automated or near-real-time analyses, but their broader adoption remains constrained by heterogeneous data formats, limited interoperability, and insufficient reporting on training data and model performance. Similarly, ongoing sensor and platform miniaturization can enhance accessibility, increase observational density, and support less invasive monitoring, while digital twins offer new opportunities to integrate observations, models, and historical data for ecosystem assessment and adaptive management. However, the operational value of these innovations ultimately depends on standardized, comparable, and well-documented data streams. Alongside these technological developments, complementary approaches such as citizen science can further extend the spatial and temporal coverage of biodiversity observations; yet, as with technology-driven systems, their effective integration into monitoring programs relies on standardized protocols and automated or AI-assisted quality control to ensure data reliability. Without shared standards, transparent reporting, and validation under real-world conditions, both technological developments and participatory initiatives risk reinforcing fragmentation rather than delivering scalable and operational monitoring solutions.

Looking ahead, this review highlights the need for a coordinated and prescriptive path toward operational marine biodiversity monitoring and mapping. Priority actions include the development and adoption of community-wide standards for data collection, processing, and reporting; mandatory disclosure of technical and economic performance metrics; and sustained investment in open-source, cost-effective, and validated hardware and software platforms. Only through such a coordinated and prescriptive approach, addressing the gaps identified here, can technological progress be transformed into operational solutions that make marine biodiversity monitoring and conservation more inclusive, effective and impactful.

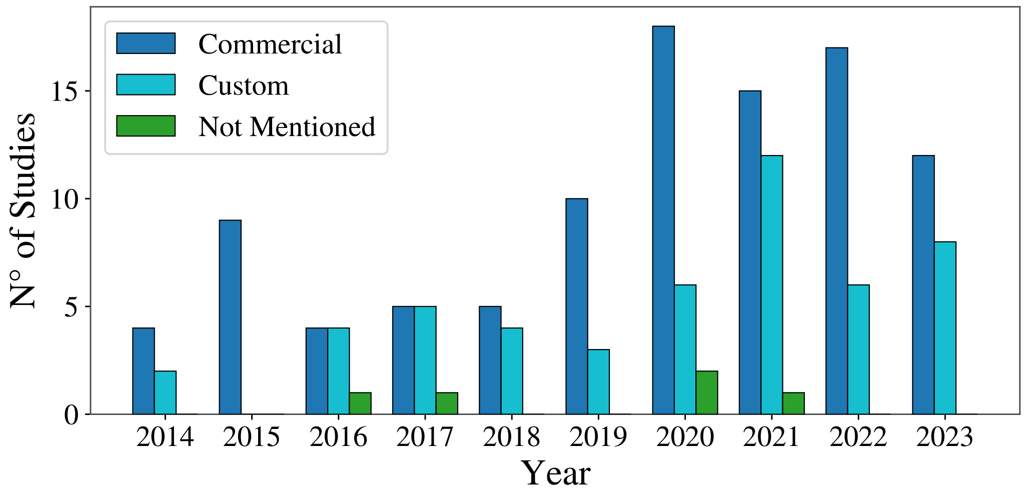

Fig. 19. Temporal trend in the use of Commercial vs. Custom technologies. While commercial solutions still stand out as the most reliable solution, some articles are using custom made devices for their studies. As for temporal trends, 2024 was kept out for better representation.

CRediT authorship contribution statement

Gennaro Ucciero: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marzia Cianflone:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Andrea Capuozzo:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Francesco Wanderlingh:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Andrea Tiranti:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Francesca Acampa:** Writing – review & editing, Visualization, Investigation. **Giovanni Indiveri:** Supervision, Resources, Funding acquisition. **Vincenzo Lippiello:** Supervision, Resources, Funding acquisition. **Simonetta Fraschetti:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT in order to improve language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This project was funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4 - Call for tender No. 3138 of 16 December 2021, rectified by Decree n.3175 of 18 December 2021 of Italian Ministry of University and Research funded by the European Union – NextGenerationEU, Award Number: Project code CN_00000033, Concession Decree No. 1034 of 17 June 2022 adopted by the Italian Ministry of University and Research, CUP B43D21010590004 Project title "National Biodiversity Future Center - NBFC"; the LIFE24-PRE-IT-LIFE MAPPER Project (101213793); and BIOBOOST+ (BIODIV22 00238)

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.marpolbul.2026.119432.

Data availability

Data will be made available on request.

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