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Multifrequency seafloor acoustic backscatter as a tool for improved biological and geological assessments – updating knowledge, prospects, and challenges

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Multibeam echosounders (MBES) have emerged as a primary tool for seafloor mapping over the past three decades. Technological advancements and improved data processing methods have increased the accuracy and spatial resolution of bathymetric measurements, and have also led to the increasing use of MBES backscatter data for seafloor geological and benthic habitat mapping applications. MBES backscatter is now frequently used to characterize habitat for marine flora and fauna, contribute to the development of effective marine spatial planning and management strategies, and generally better classify the seabed. Recently, further technological advances have enabled the acquisition and analysis of backscatter at multiple sonar operating frequencies (multifrequency backscatter), with follow-on potential benefits for improved seafloor characterization and classification. This review focuses on the currently available peer-reviewed papers related to multifrequency seafloor acoustic backscatter, providing a comprehensive summary of the contributions across different benthic environments, setting the stage for related applications and outlining challenges and research directions.

KEYWORDS

multifrequency backscatter, seafloor mapping, multispectral, multibeam echosounder, benthic habitat mapping

1 Introduction

Over the past three decades we have witnessed significant improvements in our understanding of the seabed environment through the application of high-resolution mapping technologies (Misiuk and Brown, 2024). Over this period, acoustic remote sensing techniques have continued to improve and are now more widely employed, enabling thematic mapping that can provide a wide suite of societal benefits (Harris and Baker, 2020). However, we are approaching the halfway point of the Ocean Science

Decade but are still a long way from achieving one of its priority targets: an atlas of the oceans comprising bathymetric information and multi-use thematic maps (Ryabinin et al., 2019). Accordingly, Schrodt et al. (2019) and Dolan et al. (2022) highlight the concept of Essential Geodiversity Variables (EGVs), which are associated with the geomorphology, geology, and biology of the marine environment. Among the EGVs defined for climate issues in the context of the United Nations Sustainable Development Goals, none describe the seabed.

This lack of attention overlooks the importance of depth and acoustic seafloor backscatter as essential variables for better understanding and exploring the seafloor. Bathymetry has been recognised as a very important geodiversity variable, reflected by global efforts to compile bathymetric data (Seabed 2030, GEBCO). Using concepts of multiscale morphometric analyses on bathymetry (Wilson et al., 2007), improved seafloor habitat mapping has been established by integrating multiscale derivatives and environmental data (Misiuk et al., 2021; Nemani et al., 2022). The use of backscatter as a proxy for variables associated with the geodiversity of the seabed is also increasingly common (Harris and Baker, 2020; Misiuk and Brown, 2024). Sophisticated analytical seafloor mapping techniques have been tested using backscatter data sets for the creation of thematic maps, including: image-based analysis methods (Diesing et al., 2016; Ierodiaconou et al., 2018); angular range analysis and modeling approaches (Jackson et al., 1986; Chakraborty et al., 2000; Fonseca and Mayer, 2007; Haris et al., 2011); statistical (de Moustier, 1986; Simons and Snellen, 2009), heuristic approaches using generic seafloor acoustic backscatter models (Lamarche et al., 2011), or combined approaches (Che Hasan et al., 2014). These techniques have prove to be effective at enhancing models that aim to characterize, monitor, and classify the seabed (Ierodiaconou et al., 2018; Porskamp et al., 2022). Recently, some approaches have been further improved by acquiring backscatter data at multiple different sonar frequencies.

A brief historical overview reveals that the inversion of acoustic data into physical properties of the seabed has been studied since at least the 1960s (McKinney and Anderson, 1964; Nafe and Drake, 1961). Prior to the widespread use of MBES technology, acoustic backscatter research using single-beam (Luskin et al., 1954; Knott and Hersey, 1957) and side scan sonars (Chesterman et al., 1958; Clay et al., 1964; Flemming, 1976; Mitchell, 1993) made significant advances towards improved seabed characterization. These remain as valuable tools for various applications (Hamouda et al., 2024). Pioneering work in multifrequency underwater acoustics has proposed to exploit the added value of using several frequencies simultaneously for applications in fisheries research (Korneliussen et al., 2008), seafloor characterization (Williams et al., 2009), and underwater unexploded ordnance classification (Kargl et al., 2010).

Over the past three decades, MBES backscatter has emerged as a primary multipurpose ocean mapping tool (Menandro and Bastos, 2020; Misiuk and Brown, 2024). The utility of MBES backscatter for habitat mapping has motivated the formation of the GeoHab Backscatter Working Group (BSWG) in 2013, which produced a document outlining guidelines and recommendations for the acquisition, processing, and analysis of backscatter data (Lurton et al., 2015). This document outlines a series of best practices that is openly available to the international community working with and on MBES backscatter data. The BSWG report (Lurton et al., 2015) was followed by a special issue on MBES backscatter in *Marine Geophysical Research* (Volume 39, Issue 1–2, 2018), and the use of MBES backscatter data for habitat characterization was featured prominently in the GeoHab Atlases (Harris and Baker, 2012; 2020).

Seafloor backscattering strength from MBES systems is complex and is controlled by the angle of incidence across the swath, the physical properties and roughness of the seabed, and depends strongly on the operating frequency of the sonar (Urick, 1954; Jackson et al., 1986). Additionally, MBES backscatter data is typically uncalibrated, and large-coverage surveys are often collected over multiple survey campaigns using multiple systems sometimes operated at different frequencies. This can pose challenges when processing and integrating the backscatter data sets for down-stream thematic map production (Lurton et al., 2015). However, some researchers have recognized the complexities of the frequency response of the seafloor as an opportunity for enhanced seabed characterization. Diesing et al. (2016), for example, liken the use of multifrequency backscatter to wideband satellite remote sensing, wherein the simultaneous acquisition of backscatter data at multiple frequencies provides greater detail than any single frequency alone. Although there is no universally accepted definition, we will adopt the term “multifrequency backscatter” when referring to acoustic seafloor measurements surveyed with MBES at more than one operating frequency. A multifrequency backscatter dataset can therefore be obtained using: 1) a single sonar in a single survey operating at multiple frequencies over the same area of seafloor; or 2) more than one sonar operating at different frequencies either at the same time, or operated in sequential surveys over the same area. It should be noted, however, that other terms are used in the literature when referring to multifrequency backscatter data sets (e.g., multispectral, multiband), but these terms will be avoided in this review to avoid confusion. Additionally, the term “multisource” is used in this review in reference to contiguous MBES data compiled from separate surveys that utilize multiple sonar systems, potentially of various operating frequencies, sometimes over multiple years, to cover an area of the seafloor, but where the majority of the seabed within the mapped area is surveyed at only one operating frequency. “Multisource” data sets typically comprise small areas of overlap between discrete survey data sets where the seafloor is ensonified by more than one MBES system, which may or may not be at different operating frequencies. This allows the opportunity to conduct backscatter harmonization to normalize the backscatter intensities across data sets using data from the area of overlap (see Misiuk et al., 2020; Haar et al., 2023), with follow-on benefits for benthic habitat mapping (Misiuk et al., 2024). Studies using multisource data sets therefore also provide insights into the way that MBES data sets that use multiple frequencies over the same area of seabed can offer improved understanding of benthic systems.

Since the recent availability of commercial multifrequency MBES systems, a number of studies have investigated the potential advantages and limitations of multifrequency backscatter acquisition (see Table 1 in results section). The 2017 R2Sonic Multispectral Challenge provided the first widely accessible multifrequency MBES dataset (Brown et al., 2019), inspiring a number of experiments exploring the potential of multifrequency data for seafloor classification. Within the scientific literature, multifrequency backscatter applies not only to MBES systems, but also singlebeam (Cutter and Demer, 2014; Weber and Ward, 2015; Fezzani et al., 2021), side scan sonar (Ryan and Flood, 1996; Tamsett et al., 2016; Fakiris et al., 2019) and synthetic aperture side scan sonars (Rymansaib et al., 2019). Nevertheless, this review focuses on multifrequency MBES backscatter–a relatively recent topic compared to other multifrequency technologies, which has been the topic of research of different research groups and is being actively researched by the BSWG (Brown et al., 2022). Lecours et al. (2025) identified a growing interest in these datasets by analyzing some community-drive priority questions related to multifrequency backscatter (such as "what are the bottom characteristics that are influencing multispectral responses," and some related to prediction accuracy). However, a relevant gap has been identified in terms of setting the stage for the current state of the art by providing a comprehensive overview of the main themes investigated with multifrequency backscatter. This review outlines existing contributions related to the use of multifrequency MBES backscatter in different benthic environments to explore the potential benefits offered by this technology for multiple applications (such as those related to marine spatial planning and sustainable management), to identify new research directions, and to highlight outstanding and future challenges in this field of research.

2 Methodology

To retrieve the relevant literature related to multifrequency MBES, a scientific literature review was conducted using multiple databases including Scopus, IEEE Xplore and Elsevier. Minor manual additions were made using Google Scholar. The search strings "multibeam backscatter multifrequency," "multibeam multispectral backscatter" and "multibeam backscatter multiband" were used to retrieve relevant papers. No specific time cut-off was considered, given that the majority of the works are relatively recent in terms of the specific technology addressed. Relevant publications were then selected that i) were peer-reviewed; ii) were written in English; and iii) employed multifrequency acoustic MBES backscatter (e.g., not multispectral Lidar, Radar, or satellite images). We acknowledge the importance of technical reports, atlases, and books produced by government agencies and geological surveys around the globe, but in order to adhere to a procedure (see, for example, Atkinson et al., 2015), the focus was exclusively on peer-reviewed scientific papers. A wider search contemplating additional literature and non-English publications would provide a more complete overview, but such additional methodological effort is not suitable herein.

The search was concluded in November 2024, with a total of 29 articles retained for analysis. From these, we extracted information such as location of the survey, the sonar operating frequency, whether a single or multiple sonars were utilized, and the seabed type investigated. Finally, publications were categorized into four themes based on their focus: 1) substrate/habitat classification; 2) cross-calibration/processing techniques; 3) multi-source dataset harmonization; and 4) seafloor characterization. Some papers were assigned to more than one theme.

3 Results

Table 1 provides a comprehensive listing of all the 29 references related to MBES multispectral/multi-frequency backscatter identified and a summary of the information extracted.

The reviewed literature revealed that the majority of studies were conducted on substrates such as sand, mud, and gravel (Table 1), but that the multifrequency response of several other seafloor types have also been investigated including rhodolith beds (Menandro et al., 2023), reefs (Menandro et al., 2024), and hydrocarbon seeps (Mitchell et al., 2018). The majority of studies reviewed employed high frequencies (here considered >90 kHz), indicating a prevalence of shallow-water investigations, with few studies exploring deep-water applications with multiple lower frequencies–for example, 12–44 kHz (although see Mitchell et al., 2018).

The geographical distribution of the study sites represented in this review (Figure 1) indicates limited geographic coverage. Some nations that are active in the field of seabed mapping and classification using backscatter (e.g., Norway, Australia, China, Belgium) were not captured in this review due to a lack of published peer-reviewed literature to date–though a number of well-known conference publications exist (e.g., Hughes Clarke et al., 2008; Hughes Clarke, 2015). This is partly a function of the recent and continued emergence of the field.

The importance of the R2Sonic Multispectral Challenge datasets for stimulating multifrequency MBES research was evident from this review. Seven publications by different research groups returned from the literature search were associated with these datasets (Table 1). Data from other MBES systems such as Norbit (Kruss et al., 2023), Kongsberg, and Reson have also been analyzed in some cases, but there is a gap regarding comparison of different multifrequency and multi-source MBES systems operating in the same frequency range at the same site (e.g., Malik et al., 2019). Quality control, standardization, and calibration procedures for different systems and manufacturers have emerged as priority research questions in the field (Lecours et al., 2025).

Most of the publications reviewed relate to the theme of "substrate/habitat classification," with 16 articles covering this topic (Table 1). Eleven papers focused on "seafloor characterization." Only four and three papers address "multi-source dataset harmonization" and "cross-calibration/processing techniques," respectively (Table 1). Studies related to the former were limited geographically to Canada and Italy; the latter occurred in France and the United States. While the paucity of work in these domains suggests the difficulty of utilizing multi-source datasets and attaining absolute backscatter values, it also indicates substantial scope for further exploration and extraction of useful information from legacy datasets.

4 Synthesis, prospects and challenges

A frequent conclusion of multifrequency backscatter analyses is that these datasets have enhanced our ability to characterize and

TABLE 1 Summary of references related to MBES multifrequency backscatter encountered in the scientific literature.

References	Seabed type	Frequencies (kHz) and MBES system		Dataset location	Theme
Bai et al. (2023a)	Sand (fine to coarse)	90, 300	R2 Sonic 2026	Netherlands	Substrate/habitat classification
Bai et al. (2023b)	Sand (fine and medium)	90, 200, 300, 450	R2 Sonic 2026	Netherlands	Substrate/habitat classification
Brown et al. (2019)	Mud, cobble, boulder, gravel	100, 200, 400	R2 Sonic 2026[a]	Canada	Seafloor characterization
Buscombe and Grams (2018)	Sand, mud, gravel	100, 200, 400	R2 Sonic 2026[a]	Canada	Substrate/habitat classification
Costa (2019)	Rock, cobble, mud	100, 200, 400	R2 Sonic 2026[a]	Canada	Substrate/habitat classification
Cutcliffe et al. (2024)	Boulder, cobble, pebble, sand/mud	100, 200 and 270	R2 Sonic 2026	Canada	Substrate/habitat classification
Eleftherakis et al. (2018)	Gravelly sand mixed with coarse elements, fine to medium sand, mud	200, 300	Kongsberg EM 2040	France	Cross-calibration/processing techniques
Feldens et al. (2018)	Sand	200, 400, 600	Norbit iWBMSe	Germany	Seafloor characterization
Gaida et al. (2018)	Hardground, gravel, sand, mud	100, 200, 400	R2 Sonic 2026[a]	Canada	Substrate/habitat classification
Gaida et al. (2020)	Sandy mud, sand, sand with shells	90, 100, 200, 300, 450 (for one study area); 90, 170, 255, 350 and 425 (second study area)	R2 Sonic 2026	Netherlands	Seafloor characterization
Haar et al. (2023)	Silt, sand, clay, gravel	70–300	Multi-source	Canada	Multi-source dataset harmonization
Janowski et al. (2018)	Sand, gravel, boulder	150, 400	Norbit iWBMS	Poland	Substrate/habitat classification
Khomsin et al. (2024a)	Silt and sand	200, 300, 400	R2 Sonic 2020	Indonesia	Substrate/habitat classification
Lacharité et al. (2018)	Mud, sand, gravel, glacial till	70–100, 100, 300	Multi-source	Canada	Multi-source dataset harmonization; substrate/habitat classification
Menandro et al. (2022)	Mud, sand	170, 280, 400, 700	R2 Sonic 2024	Brazil	Substrate/habitat classification; seafloor characterization
Menandro et al. (2023)	Rhodolith	170, 280, 400	R2 Sonic 2024	Brazil	Substrate/habitat classification; seafloor characterization
Menandro et al. (2024)	Reefs	170, 280, 400, 700	R2 Sonic 2024	Brazil	Seafloor characterization
Misiuk et al. (2020)	Mud, sand, gravel	100, 200, 400	R2 Sonic 2026[a]	Canada	Multi-source dataset harmonization
Misiuk and Brown (2022)	Mud, sand and gravel	100, 200, 400	R2 Sonic 2026[a]	Canada	Substrate/habitat classification
Mitchell et al. (2018)	Hydrocarbon seeps	12, 30, 200	Kongsberg EM122, EM302, EM2000	United States	Seafloor characterization; cross-calibration/processing techniques
Ntouskos et al. (2023)	Mud, sand, mixed sediment, coarse sediment	100, 200, 400	R2 Sonic 2026[a]	Canada	Substrate/habitat classification
Prampolini et al. (2021)	Mud, sand, rhodolith, reef, boulder, bedrock	30–300	Multi-source	Italy	Multi-source dataset harmonization; substrate/habitat classification
Runya et al. (2021)	Gravel, sand	30, 95, 300	Kongsberg EM3002, EM302, EM1002	United Kingdom	Seafloor characterization
Runya et al. (2024)	Gravel, sand	95 and 300	Kongsberg EM3002, EM1002	United Kingdom	Substrate/habitat classification
Schulze et al. (2022)	Sand, gravel (seagrass, mussel reef)	200, 400, 550, 700	Norbit iWBMS	Germany	Seafloor characterization
Spain et al. (2022)	Sand, silt, hardgrounds	30, 200	EM302, EM2040	New Zealand	

(Continued on following page)

TABLE 1 (*Continued*) Summary of references related to MBES multifrequency backscatter encountered in the scientific literature.

References	Seabed type	Frequencies (kHz) and MBES system		Dataset location	Theme
					Substrate/habitat classification; seafloor characterization
Trzcinska et al. (2020)	Sand, boulder	150, 400	Norbit iWBMS	Poland	Substrate/habitat classification
Schneider von Deimling et al. (2013)	Mud (shallow gas)	12, 95	Kongsberg EM120, EM1002, ATLAS Parasound	Germany	Seafloor characterization
Wendelboe (2018)	Sand	190–400	Reson	United States	Cross-calibration/processing techniques

[a]Dataset from R2Sonic Multispectral Challenge.

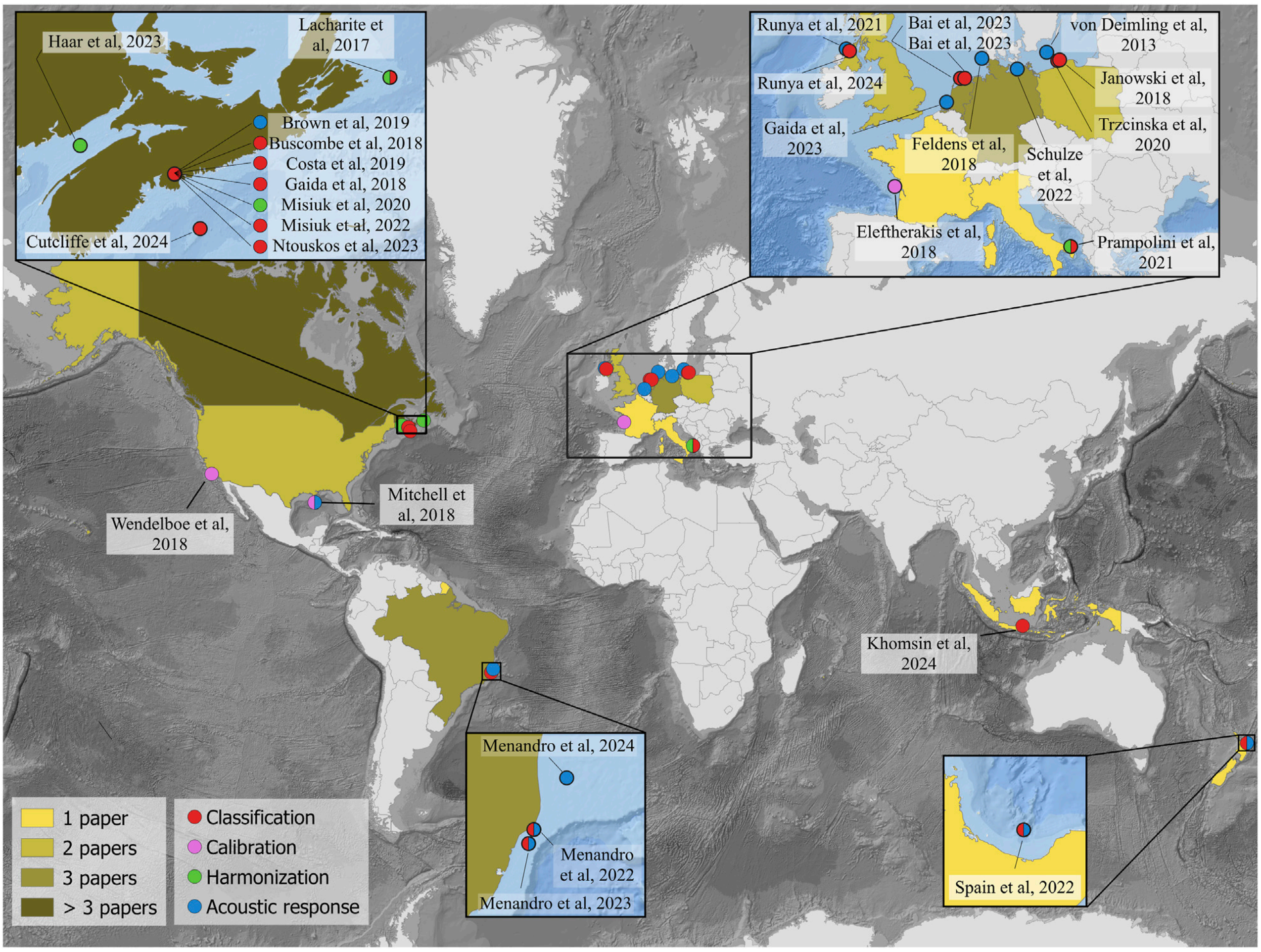

FIGURE 1
Geographical distribution of papers on multispectral backscatter until August 2024, classified according to main theme (substrate/habitat classification, cross-calibration/processing techniques, multi-source dataset harmonization, and seafloor characterization based on acoustic response).

classify the seabed from geological and biological perspectives. Brown et al. (2019), Costa (2019), and Menandro et al. (2022) highlight this for finer-grained sediments, and the benefits of multifrequency datasets have also been observed for other bottom types (Schulze et al., 2022; Spain et al., 2022). While higher frequencies are commonly useful for detailed mapping of surficial sediments (Mitchell et al., 2018; Janowski et al., 2018), lower frequencies may also be informative (Hughes Clarke, 2015; Feldens et al., 2018; Schneider von Deimling et al., 2013). In some cases, lower frequencies have even demonstrated greater ability to discriminate between sediment types (Gaida et al., 2018; Feldens et al., 2018). We note that, without a subsurface vehicle though (e.g., Mitchell et al., 2018), multifrequency applications are greatly limited in deeper waters by the ability of the signal to reach the bottom. Low frequencies (e.g., <30 kHz) are commonly used in such cases, yet these signals may easily penetrate metres into soft sediments (Mitchell, 1993; Schneider Von Deimling et al., 2013). Frequencies > 100 kHz are fully attenuated within 1 m of sediment, enabling their use for surficial multifrequency characterization, but limiting these applications to shallow waters. This is a technical limitation that is unlikely to be resolved for ship-borne mapping; the literature reviewed here thus primarily concerns high frequency sounding in shallower waters.

While the application of multiple frequencies does not always yield better distinction or classification results (see Runya et al., 2021; Menandro et al., 2023; Bai et al., 2023b; Runya et al., 2024), it may allow us to identify the most useful frequency to characterize a specific benthic environment that could be missed from a single frequency survey (Cutcliffe et al., 2024). Gaida et al. (2018) propose that a combination of 100 and 400 kHz yields comprehensive insights into seabed characteristics, yet the optimal frequency for acoustic-based classification is dependent on the specific characteristics of the local seabed. Runya et al. (2021) observed a stronger correlation between backscatter strength and mean grain size at 30 kHz than 300 kHz when examining a seafloor that ranged from sand to gravel. Bai et al. (2023b) did not observe this contrast at 90 and 300 kHz in study areas that were predominantly composed of sand. Menandro et al. (2023) observed that higher frequencies (280 and 400 kHz) exhibited enhanced sensitivity in detecting the presence of rhodoliths, but a lower frequency (170 kHz) proved more effective in characterizing abundance. Schulze et al. (2022) found that higher frequencies are optimal for discriminating coarse sand against gravel, while lower frequencies are susceptible to fluctuations in the shallow subsurface.

Limitations inherent to multifrequency surveys have also been previously identified. One such limitation is that the survey depth is constrained by the attenuation of the highest frequency. This can be overcome in some cases through the use of autonomous vehicles to obtain higher resolution data sets in the deep sea using higher operating frequencies (Mitchell et al., 2018). Additionally, the use of multiple frequencies may negatively impact resolution in the along-track direction when conducting a multifrequency survey on a ping-by-ping basis. Brown et al. (2019) configured the sampling rate of the sonar high enough to counter the along-track reduction in data density and did not observe any loss in the resolvability of seafloor features when compared against single frequency MBES backscatter mosaics. Another alternative technological solution to avoid reduction of along-track resolution when collecting multfrequency backscatter is the use of transmitted chirp signals and construction of multifrequency information on the receive signal (Trzcinska et al., 2021), although this technique provides fewer spectral bands compared to ping-by-ping modulation (e.g., Brown et al., 2019). Multifrequency data obtained using a single frequency over multiple passes presents difficulties related to the precise co-location of ensonification geometries and potential alterations in the seafloor over time (Montereale-Gavazzi et al., 2019). The use of single source multifrequency acquisition eliminates the potential issues associated with discrepancies in sonar configuration and survey geometry. Finally, MBES multifrequency surveys are limited to the lower frequency end by transducer design, wherein larger transducer arrays (up to several m in size) are necessary to operate below 20 kHz.

Some studies indicate that utilizing multifrequency data is non-trivial. In some cases, it is possible that the acoustic response of different acoustic frequencies depends on different sediment layers, which may display different backscattering due to signal penetration into the seafloor (Kohmsin et al., 2024b). Towards the outer beams, where the signal intersects the seabed at a higher incidence angle, it is increasingly difficult to separate the influences of surface and volume scattering. However, these challenges may offer an opportunity to investigate new metrics related to the relationships between frequencies (Misiuk and Brown, 2022). Schneider von Deimling et al. (2013) demonstrated that bathymetric measurements obtained at 12 kHz exhibited depth values that were systematically deeper by several meters in relation to those acquired at 95 kHz. Gaida et al. (2020) observed that the measured bathymetry and backscatter at different frequencies corresponded to different parts of the seabed. The authors argue that if the signal penetration and scattering (and unknown subsurface attenuation and refraction) from buried structures are not considered, multifrequency MBES data can also lead to ambiguous interpretations of the surficial seafloor.

Multisource legacy backscatter data represent a valuable resource for regional seabed mapping. However, the discrepancies associated with different sonar systems, frequencies, and software, have led to the development of approaches to synthesize and harmonize multiple datasets to meet management needs (Lacharité et al., 2018; Misiuk et al., 2020; Prampolini et al., 2021; Haar et al., 2023). Hughes Clarke et al. (2008) highlighted that these issues will persist in the compilation of seabed backscatter strength maps for an extended period, given the continuous upgrades of sonar systems. In this context, backscatter calibration studies also have potential to address and mitigate these inconsistencies, thereby facilitating the comparison of mosaics created from different acoustic sources. Backscatter calibration studies are still relatively scarce, even considering MBES single-frequency datasets (e.g., Fezzani et al., 2021), and have been incorporating a larger range of variables such as temperature (Van Dijk et al., 2024).

Technological development in the field of underwater acoustics has facilitated the investigation and enhancement of seabed classification techniques over the past few decades (Kenny et al., 2003; Robert et al., 2017; Strong et al., 2019; Misiuk and Brown, 2024). This has produced a range of tools based on diverse data sources and multidisciplinary approaches, which enables comprehensive geospatial modeling of seabed types and habitats. Methods for seabed classification using acoustic variables is still a very active field of research (Diaz et al., 2004; Brown et al., 2011; Lecours et al., 2016; Misiuk and Brown, 2024). Early approaches were interpretative, and technologies such as RoxAnn and QTC-View offered substantial advances through automated data-driven approaches (Hamilton et al., 1999; Foster-Smith et al., 2004; Brown

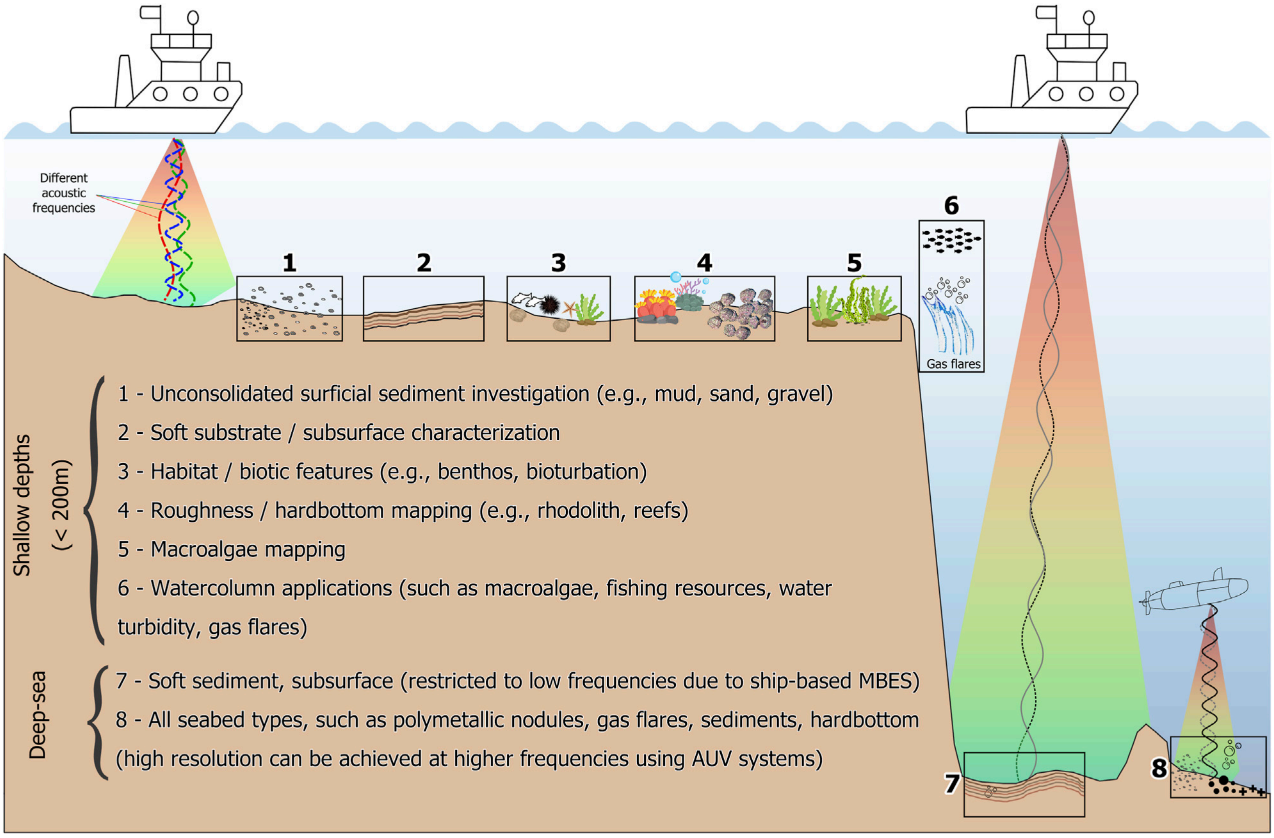

FIGURE 2
Multifrequency backscatter may enable better characterization of certain substrates and features across different benthic environments (1-6 shallow environments, 7-8 deep-sea environments). Currently, most multifrequency backscatter research is confined to shallow water (<200 m).

et al., 2005). Recently advances have yielded increasingly robust and accurate models capable of supporting large data inputs, with MBES backscatter as a frequent component (Stephens and Diesing, 2014; Trzcinska et al., 2020; Cui et al., 2021; Misiuk and Brown, 2022; Garone et al., 2023). In addition to the development of approaches utilising mosaics or angular responses, multifrequency backscatter data has enabled analyses of the multifrequency response of the seafloor based on the creation of multiband false color mosaics, similar to those employed in satellite remote sensing. While distinct patterns in such datasets have been observed in some instances (Feldens et al., 2018; Schulze et al., 2022; Menandro et al., 2022), their meaning is generally not fully understood.

While novel technologies have enabled the acquisition of larger datasets (at higher resolutions and often including water column backscatter data) increasing data volumes have also introduced analytical challenges. Very large data volumes from modern MBES systems now require methods for extracting and summarising information in an efficient and meaningful way. This issue is compounded when the expansive selection of potential textural, angular response, composite, depth, and morphometric features are considered–each of which may be considered in multiples when utilizing multifrequency data. We believe that deep neural network approaches have great potential to optimize the analysis of such multi-dimensional and multivariate MBES datasets (Misiuk et al., 2021; Arosio et al., 2023; Garone et al., 2023), providing an opportunity to efficiently explore geospatial modelling by employing a deep convolutional architecture.

The work reviewed here suggests that continued improvements to multifrequency MBES technologies and techniques have great potential to provide better characterization of both surficial and sub-surface seafloor attributes (Figure 2). The application of multifrequency backscatter can support a number of critical topics that are aligned with international priorities such as the UN Decade of Ocean Science, including site characterization for offshore wind farms, habitat mapping for conservation and management, identification of fluid mud in ports, natural resource mapping, and marine spatial planning. Multifrequency backscatter may support these initiatives through textural sediment characterization (Runya et al., 2021; Menandro et al., 2022; Misiuk and Brown, 2022); investigations of the seabed subsurface (Schneider von Deimling et al., 2013; Gaida et al., 2020); mapping of biotic features and habitats (Feldens et al., 2018; Bai et al., 2023b; Runya et al., 2024; Cutcliffe et al., 2024); rough and hardbottom characterization (Menandro et al., 2023; Menandro et al., 2024); macroalgae mapping (Schimel et al., 2020; Menandro et al., 2024); water column applications (Spain et al., 2022; Guedes et al., 2024); and deep sea mapping with remote vehicles (e.g., Mitchell et al., 2018; Gazis et al., 2024). In the future, it may even be feasible to catalog and link multifrequency patterns to specific habitats or even individual species, similar to approaches used in multispectral satellite remote sensing.

Author contributions

PM: Conceptualization, Formal Analysis, Methodology, Writing–original draft. BM: Conceptualization, Formal Analysis, Writing–review and editing. JS: Conceptualization, Writing–review and editing. AB: Conceptualization, Writing–review and editing. CB: Conceptualization, Funding acquisition, Writing–review and editing.

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Conflict of interest

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