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Development of deep-sea mining and its environmental impacts: a review

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With the increasing demand for mineral resources and the continuous depletion of terrestrial mineral deposits, deep-sea mining has garnered significant attention from governments, industries, and research institutions. However, the current deep-sea mining technologies remain incompletely developed, and their environmental impacts cannot be overlooked. This review presents a brief introduction to the three primary mineral resources found in the deep sea and the relative deep-sea mining system, along with their potential environmental risks. As the deep-sea benthic ecosystem is particularly vulnerable, the impacts on environment of each phase of deep-sea mining should be monitored and controlled. The movement and operation of seafloor mining vehicles generate both direct and indirect environmental impacts, including seabed destruction and plume generation. These effects pose significant threats to benthic organisms and alter the deep-sea environment. Finally, we present future perspectives and insights for subsequent research and the industrialization of deep-sea mining.

KEYWORDS

deep-sea mining, mineral distribution, mining technology, environmental impact, monitoring and assessment

1 Introduction

In recent years, global industrialization has resulted in the rapid depletion of terrestrial mineral resources, which are increasingly becoming scarce. The oceans, covering 70% of the Earth's surface, are abundant in mineral resources, such as polymetallic nodules, massive sulfides, and cobalt-rich crusts. The resource reserve of polymetallic nodules in the Clarion-Clipperton Zone (CCZ) of the Pacific Ocean is estimated to be 5 to 10 times greater than that of global terrestrial reserves. These extensive metal resources are essential for the advancement of modern society (Fan et al., 2022). Deep-sea mineral resources are plentiful and possess vast reserves that could meet global consumption for hundreds or even thousands of years, making them a valuable asset for promoting sustainable development.

Their extraction and use are destined to be inevitable trends for the future development (Ju et al., 2023).

We searched publications from 1 January 1971 to 31 December 2024 using the Web of Science Core Collection with the keyword "ocean mineral sources". The results are shown in Figure 1. A total of 9,650 valid bibliographic records were obtained, and the total number of published articles increased each year. The trend in the number of articles published annually can be divided into three periods: the first period was from 1990 to 1997, when the number of publications was below ten per year and at a low point. The second period occurred from 1998 to 2003, with the annual publication volume fluctuating between 20 and 100. In the third period, from 2004 to 2024, the number of publications exceeds 100 per year. Particularly in recent years, the number of publications has significantly increased, indicating that "marine mineral resources development" has become a popular research topic in the past decade. Moreover, these trends may indicate that this research topic will remain prominent for a long time in the future.

Although the concept of deep-sea mining was proposed as early as the 1960s, its industrialization has not been realized yet. Environmental pollution and sustainable development have become the most significant constraints on its advancement (Ma et al., 2022). Deep-sea ecosystems are characterized by rich biodiversity and complex ecological relationships, with benthic ecosystems encompassing various habitats such as seamounts, deep-sea basins, mid-ocean ridges, and continental slopes. These ecosystems provide important ecosystem services, such as carbon sequestration and nutrient cycling (Liu et al., 2022). The exploration and extraction processes of deep-sea mineral resources can cause multiple potential harms to the surrounding environment, including altering seabed topography, destroying habitats for benthic organisms, and generating noise pollution in the water (Kun et al., 2024). Therefore, studying and solving the environmental impacts of deep-sea mining is crucial for achieving its industrialization and sustainable development.

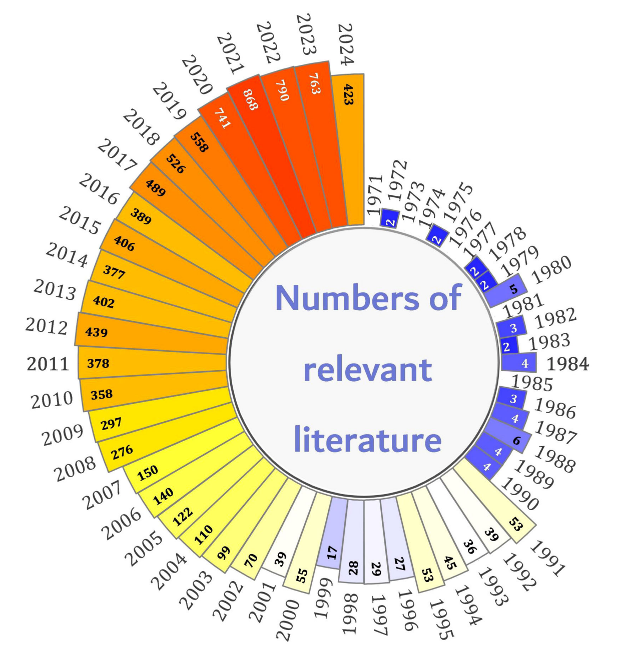

FIGURE 1
Trends in publications.

2 Main types and operational methods of deep-sea mining

2.1 Types and distribution of seabed minerals

2.1.1 Polymetallic nodules

Polymetallic nodules, also known as ferromanganese nodules or manganese nodules, are a potential seabed mineral resource primarily composed of Fe and Mn, along with significant amounts of Ni, Cu, Co, Mo, Li and other elements. They play a vital role in applications such as photovoltaic cells and catalytic technologies (Miller et al., 2018). The growth rate of polymetallic nodules is extremely slow, 34with only a few millimeters to centimeters of growth occurring over a million years. Individual nodules typically grow around a central core, forming spherical, ellipsoidal, or irregular shapes, with diameters ranging from 1 cm to 10 cm. Polymetallic nodules are predominantly distributed across the deep-sea floors of the Pacific, Atlantic, and Indian Oceans at depths ranging from 4,000 to 6,500 m (Ju et al., 2023). Economically valuable concentrations of nodules have been discovered in the following geographic locations: CCZ in the north-central Pacific, the Peru Basin in the southeastern Pacific, and the Central Indian Ocean Basin, etc (Hein et al., 2020).

2.1.2 Massive sulfides

Seafloor Massive Sulfides are deposits formed by high-temperature hydrothermal fluids expelled from volcanic activity along mid-ocean ridges, island arcs, and back-arc basins behind active subduction zones. These deposits, rich in valuable metals such as Cu, Zn, Pb, Au and Ag, represent a highly exploitable seabed mineral resource (Zhu et al., 2020), they are primarily distributed in the Red Sea and the western Pacific Ocean (Guo et al., 2023). In regions where submarine hydrothermal activity is prevalent, large-scale sulfide deposits are often discovered, widely distributed in hydrothermal zones along mid-ocean ridges, volcanic arcs, and back-arc spreading centers at water depths ranging from 1,000 m to 3,500 m (Lalou et al., 1985). According to statistics, approximately 60% of the world's known sulfide deposits are located along mid-ocean ridges, 25% are found in back-arc basins, and 15% are situated on submarine volcanic arcs (Petersen et al., 2016).

2.1.3 Cobalt-rich crusts

Cobalt-rich crusts represent another significant deep-sea sedimentary solid mineral resource discovered following polymetallic nodules. They are primarily distributed at the summits, flanks, and broad saddle structures of seamounts at water depths ranging from approximately 800 to 3,000 m, typically firmly attached to the hard bedrock surfaces. These crusts are rich in various metallic and rare earth elements, including titanium, cerium, nickel, platinum, manganese, phosphorus, thallium, tellurium, zirconium, tungsten, bismuth, and molybdenum (Clark and Clark, 1986). Notably, their cobalt content is particularly high, reaching up to 2%, which is more than 20 times the cobalt content found in terrestrial deposits (Maksimov and Safronov, 2018). In terms of distribution, seamount regions are the primary areas of enrichment, accounting for 84.0% of the total reserves, far exceeding those found on ocean ridges, ocean basins, and continental slopes. As a result, seamounts are considered the most favorable geomorphic type for the growth of high-grade cobalt-rich crusts (Shen et al., 2021). Based on grade, reserves, and oceanographic conditions, the central equatorial Pacific, particularly within the exclusive economic zone of Johnston Island (USA), the Marshall Islands, and the international waters of the Central Pacific Seamounts, exhibits the most significant potential for cobalt-rich crust mining (Hein et al., 2013).

The economic value of these three deep-sea mineral resources is evident. Currently, they remain in the exploration and pilot mining phases. Figure 2 illustrates the spatial distribution of these four mineral deposits.

2.2 The existing equipment, technology and operation mode of deep-sea mining

Deep-sea mining is a vast and complex engineering system. Globally, the development schemes for deep-sea mineral resources are primarily categorized into drag bucket, continuous bucket line, autonomous shuttle vessel, and pipeline lift systems (Liu et al., 2014). Among these, the first three methods have been phased out due to their significant environmental impact and low mining efficiency, and are no longer being further developed or tested (Nishi, 2013). The pipeline lifting system includes hydraulic lifting and pneumatic lifting. Pipeline lifting can be integrated with remotely operated collecting vehicles, offering enhanced operational flexibility to navigate around unfavorable seabed topography and obstacles. This system presents lower technical complexity while achieving superior mining efficiency (Du et al., 2016). Thus, both domestically and internationally, the pipeline lift deep-sea mining system is predominantly adopted. The schematic diagram of this system is shown in Figure 3, it consists of three core components: the underwater collection system, the mineral lifting system, and the surface platform.

2.2.1 Underwater collection system

The underwater collection system consists of ore excavation equipment, ore crushing equipment, and ore gathering equipment (Li et al., 2022). The deep-sea mining vehicle is one of the core technological assets in deep-sea mining, designed to collect minerals from the ocean floor, separate sediments, crush nodules, and transport them to the mineral lifting system (Long et al., 2024). During the nodule fragmentation and mining vehicle operation processes, sediment plumes are generated.

The environmental impact of different locomotion and collection methods of mining vehicles varies. Theoretically, based on the seabed terrain, there are three types of locomotion: floating, towed, and self-propelled (Kang and Liu, 2021). However, deep-sea mining operations generate a certain amount of counterforce, making the floating method difficult to implement. In practice, mining vehicles utilize towed and self-propelled methods. Early

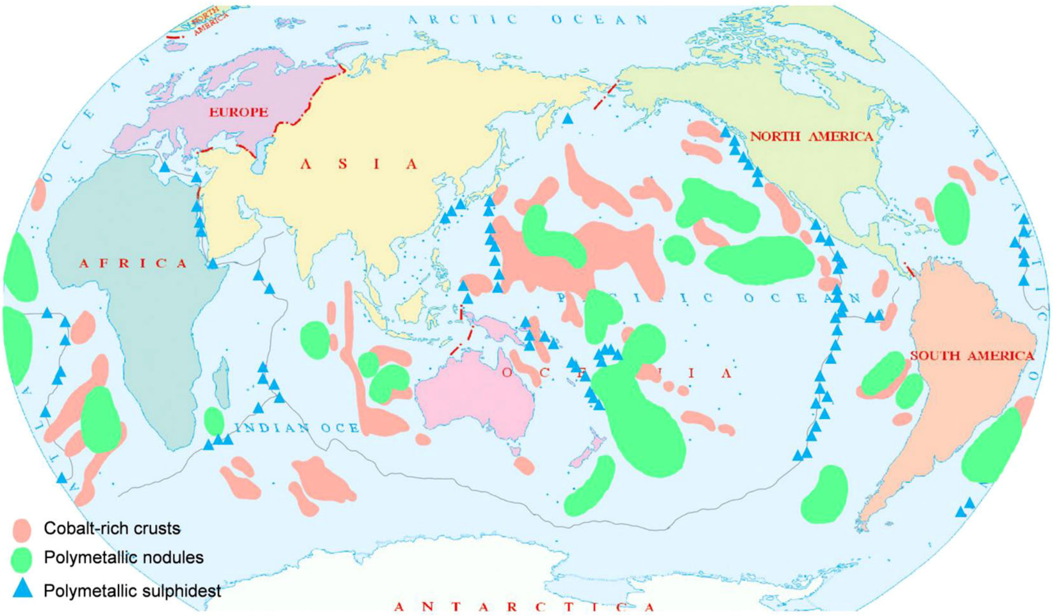

FIGURE 2
Global mineral distribution map.

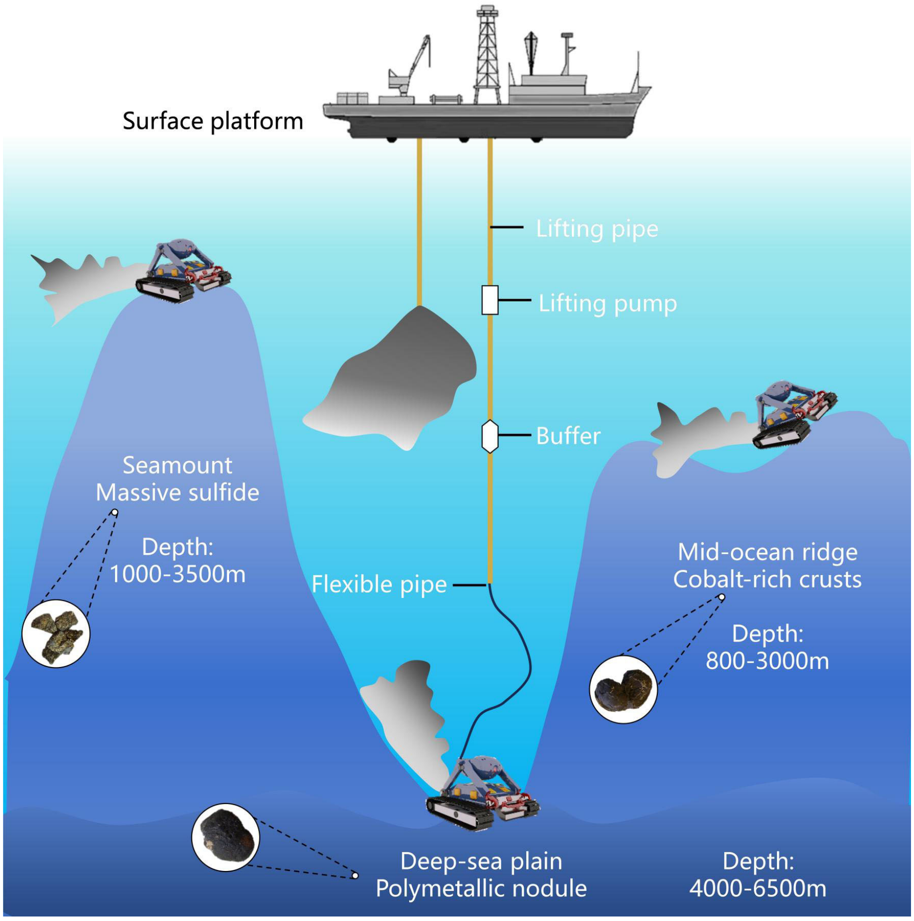

FIGURE 3
Schematic diagram of the mining system.

deep-sea mining operations employed towed seabed mining vehicles, but this method posed challenges in path control, obstacle avoidance, and had low collection efficiency. The self-propelled method includes two types: the Archimedean screw propulsion and the tracked self-propelled method. The former has a simple structure but is prone to slipping and difficult to maneuver, causing significant disturbance to the seabed (Liu et al., 2014). The tracked self-propelled method offers strong load capacity and can adapt well to harsh terrains. Consequently, most currently developed seabed mining vehicles adopt the latter method.

The excavation equipment varies depending on the type of mineral deposit. Polymetallic nodules, typically found on flat seabed and coexisting with deep-sea sediments, can be collected using mechanical, hydraulic, or hybrid mechanical-hydraulic methods. The operational principle of the mechanical collection device involves using a rotary chain-toothed mining head to excavate nodules from the seabed and transport them to the mining vehicle (Long et al., 2024). In contrast, the hydraulic collection device employs high-pressure water jets to dislodge the nodules from the seabed, followed by the use of water flow to gather them into the mining vehicle. Massive sulfides, located near hydrothermal vent areas, are generally extracted using auxiliary cutting machines or multifunctional integrated excavation equipment. Cobalt-rich crusts, which grow on bedrock surfaces, are typically mined using spiral roller excavation devices to separate them from the bedrock (Li et al., 2022). Regardless of the collection method employed, the design must meet the requirements of high collection efficiency, minimal disturbance, high operational efficiency, and low energy consumption.

2.2.2 Mineral lifting system

The mineral lifting system primarily consists of a riser system, a relay station, a flexible hose system, and a conveying power unit (Long et al., 2024). It is designed to transport the ore collected and crushed by the mining vehicle from the seabed to the mining vessel on the surface platform (Li et al., 2022). The system typically employs either hydraulic lifting or pneumatic lifting, where a lifting pump conveys the mixture of ore-seawater or ore-seawater-air to the surface support platform (Li et al., 2022). Pipeline ruptures can result in mineral and sediment leakage, contaminating mesopelagic waters. The extraction process generates acoustic disturbance, adversely impacting marine biota and ecosystem dynamics.

2.2.3 Surface platform

The surface platform includes mining vessels, transport vessels, and multi-functional support vessels, serving as the centralized control terminal for deep-sea mining operations (Long et al., 2024). On one hand, after the ore is transported to the surface, it undergoes preprocessing, dewatering, and temporary storage on the platform before being transferred to shuttle vessels. On the other hand, the surface support platform ensures the power supply, information communication, and navigation positioning of the mining system, while also functioning as the control center for mining operations (Li et al., 2022). During this process, the discharge of processed tailings into the ocean generates suspended particle plumes while simultaneously affecting physicochemical properties such as water temperature and turbidity.

3 Impacts of deep-sea mining on marine ecosystems

The extraction of deep-sea mineral resources can cause several impacts on their original environment. The process of seabed mining of nodules, sulphides or crusts relies on one or more mining tools or vehicles that collect resources and transfer them into risers. Mineral extraction, gathering, lifting, offshore processing and transportation processes all have varying degrees of impact on the seafloor, water column and surface environment of the ocean (Banakar et al., 2007), including habitat displacement, burial of sediment plumes, disturbance of sediment plumes in the water column (which may contain dissolved metals), noise and vibration (Washburn et al., 2019).

3.1 Impact on the seabed area

3.1.1 Effects of sediment disturbance

Deep-sea mining have two direct environmental impacts, leading to the immediate mortality of organisms and the severe or even permanent destruction of their benthic habitats (Weaver et al., 2022).

The movement of mining vehicles can crush organisms that growing in deep-sea sediments, as well as sponges and other filter-feeding animals (Vonnahme et al., 2020). Rolling, suction and collision damage from mining equipment kills deep-sea fish and zooplankton that are poorly mobile and unable to escape from disturbance (Koschinsky et al., 2018). In addition, mining activities extract sediments and nodules from the seafloor surface (Smith et al., 2020), altering the habitat of benthic organisms and rendering some organisms that use nodules as anchorage points homeless (Vanreusel et al., 2016). A single mining operation is projected to extract 300–700 km of nodules and twice that amount of seafloor as near-surface sediments, leading to faunal mortality in the total area that is directly mined (Radziejewska, 2002).

So far, data from numerous small-scale commercial test mines and scientific disturbance events aimed at simulating mining are available for review. For example, Germany conducted the Disturbance and Recolonization Experiment (DISCOL) in 1989 in the region of manganese nodules in the deep equatorial eastern Pacific Ocean (Thiel et al., 2001). The Benthic Impact Experiment was carried out in the United States in 1991 to evaluate the effects of sediment resuspension and deposition. The DISCOL experiment revealed that, even six months after the disturbance, certain organisms remained buried under sediment, the mobile macrofauna demonstrated low diversity and population size, and a significant number of sessile forms were nearly disappear (Sharma et al., 2001). Upon revisiting the site after 26 years, they discovered that the tracks left by mining vehicles remained visible, with reduced biodiversity along these marked pathways compared to adjacent undisturbed areas. A variety of fauna was noted throughout the disturbance experiments. In DISCOL, the number of species decreased, homogeneity decreased, and the overall diversity of macrofaunal polychaetes in each sample was less than that of the control condition. The diversity and abundance in disturbed areas showed consistently significant lower levels over a span of seven years (Sharma, 2011). A series of simulated disturbance experiments appeared a decline in the diversity and biomass of marine organisms in the disturbed area compared to the surrounding undisturbed area. This decline is particularly evident among benthic organisms, such as sponges, soft corals, and jellyfish (Vonnahme et al., 2020).

Mining activities can also damage seabed ecosystems. For example, extracting polymetallic sulfides may disturb unique benthic ecosystems that are entirely chemosynthetic and contribute to the acidification of the surrounding seawater (Hallgren and Hansson, 2021).In addition, jets used to loosen minerals can disturb sediments and create seafloor sediment plumes. These jets may permanently remove minerals and their surrounding sediments, thereby affecting fragile ecosystems in various ways (Weaver et al., 2018).

3.1.2 Resuspension of sediments

Sedimentation of sediment plumes outside mining areas can cause suffocation and burial of benthic fauna (Miljutin et al., 2011). Redeposition suspended particles and tailings can bury benthic flora and fauna, potentially leading to their death (Drazen et al., 2020). Besides, the redeposition of sediments suspended by mining activities may disturb seafloor communities. A single mining operation with a 15-year period could severely disrupt 50,000 km^2 of deep-sea communities (Ramirez-Llodra et al., 2011). For one ton of polymetallic nodules mined, 2.5 to 5.5 tons of sediment are disturbed and suspended (Amos and Roels, 1977). The resuspension and redistribution of sediments will change various parameters in the benthic environment. These sediments will not only settle in the mining area, but also be transported to neighboring regions, altering the physicochemical conditions of the seafloor and increasing the rate of deposition. Increased turbidity can also lead to the clogging of benthic filter feeders and the suffocation of less active epipelagic organisms (Sharma et al., 2001). Benthic organisms inhale numerous suspended solid particles during respiration, which is harmful to their health and survival (Pinheiro et al., 2021).Several studies have found that when organisms were cultured in water with different concentrations of suspended solids, significant enrichment of suspended solids in their organs can be observed (Leduc and Pilditch, 2013).It follows that metal ions are also enriched in organisms when added to these solid particles (Gillard et al., 2019).

3.1.3 Anthropogenic light

Light from seafloor mining equipment can disrupt bioluminescence, a crucial ecological function, and harm the eyes of living organisms (Boschen et al., 2013). High-intensity lighting from Human-Occupied Vehicles and Remotely Operated Vehicles harms shrimp photoreceptors, which allow the detection of dim light emitted by high-temperature vents. This ability acts as a method of near-field remote sensing, assisting shrimp in avoiding heat stress and mortality. Additionally, the intense human-made light may pose a major threat to the survival of this species (Copley et al., 2007).

3.1.4 Noise

Many marine animals use sound as their primary means of communication. Since sound travels more than four times faster underwater than in air and is absorbed less in water than in air, sound generated by deep-sea mining equipment may cause serious problems. The operation of mining vehicles and the movement of deep-sea minerals through pipes or chain drums generates noise in all directions. Most deep-sea species typically experience only low levels of noise, however, continuously anthropogenic noise will significantly increase ambient sound levels (Miljutin et al., 2011), negatively affecting the normal life activities of marine organisms and potentially disturbing the communication and navigational functions of some species (Williams et al., 2022).

Marine mammal exposure experiments and noise propagation modeling indicate that hearing damage can occur at distances between 100 m and 100 km from the sound source (Southall et al., 2008). Noise can disrupt behavior (e.g., feeding, breeding, resting, migrating), mask sounds used for communication and navigation, and lead to temporary or permanent hearing loss damage (Moore et al., 2012). Meanwhile, the potential effects of noise on fish and invertebrates remain poorly understood but could be equally important (Hawkins et al., 2015).

3.2 Impact on water bodies

3.2.1 Sediment plumes

Sediment plumes are mostly produced by seafloor production tools, particularly cutters and collectors, along with risers and treated materials. The main waste generated during mineral recovery includes dewatering wastes, side-cast sediments, and sediments released during mining. Dewatering wastes may contain fine sediments and heavy metals that can be resuspended when discharged into the water column (Gollner et al., 2017). The impacts of plume generation are multifaceted, as illustrated in Figure 4. There are two main sources of sediment. One is sediment suspended by direct interaction with the turbulent wake behind the vehicle, and the other is sediment removed from the plume as it propagates laterally from the collector track.

However, deposition of particulate matter and sediments can cover large areas, and high plume concentrations can cover and bury benthic fauna(Vonnahme et al.). These sediments will not only settle in the mining area, but also be transported to regions nearby, changing the physicochemical conditions of the seafloor and

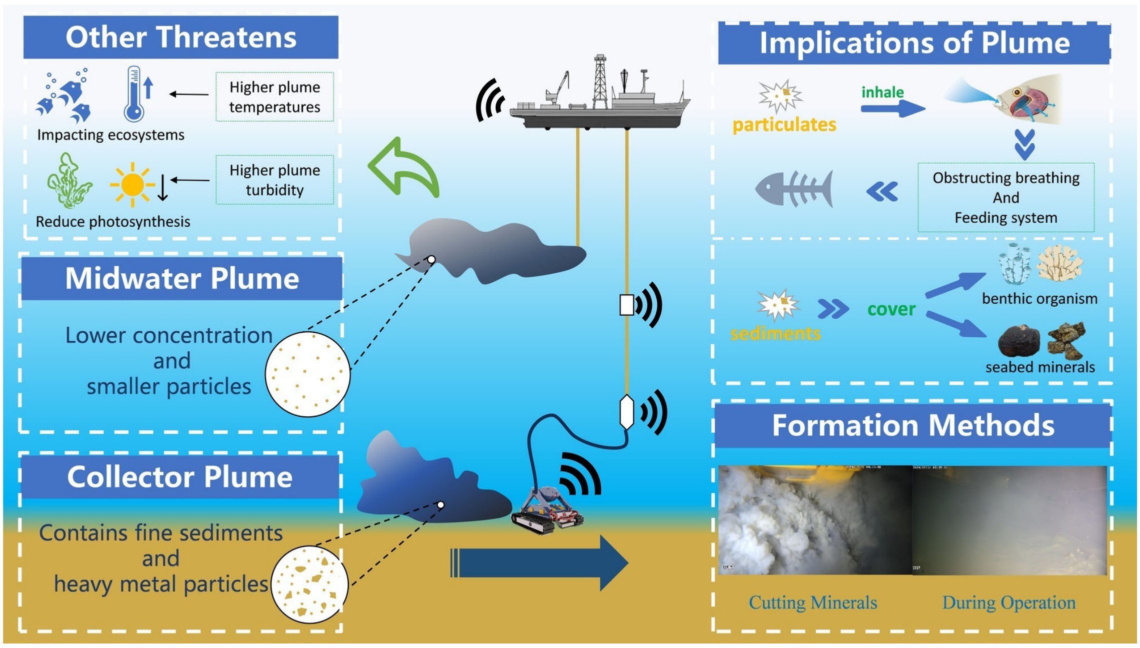

FIGURE 4
Schematic of plume impacts.

accelerating the rate of deposition. Increased turbidity can also cause clogging of benthic filter feeders, suffocating and killing less active epipelagic organisms seafloor (Mukhopadhyay et al., 2019). This asphyxiation will hinder the gas exchange and feeding structures of rootless organisms and may cause many other potential effects due to exposure to heavy metals and acid waste.

In April to May 2021, Belgian contractor Global Sea Mineral Resources NV conducted prototype nodule collector trials in the deep Pacific Ocean. The collector is equipped with numerous sensors to monitor the sediment plume near the vehicle. The monitoring results indicated that the plume generated by the operation of the deep-sea mining equipment didn't dissipate quickly, and sediment can be detected more than 3 m away after a few hours (Muñoz-Royo et al., 2022). Observations indicated that 92 to 98 percent of the sediment produced by the collector is below 2 m, with localized sediments covering nearby nodular fields, while 2 to 8 percent of the sediment is 2 m or more above the seabed.

Additionally, organisms found in deep-sea areas have adapted to low turbidity conditions. Therefore, even very low plume concentrations can affect the ecology of mining site (Weaver et al., 2022). However, effective measures to address mining-induced plumes remain elusive. Zhang et al. proposed a potential solution utilizing flocculants to accelerate particle sedimentation. Their laboratory simulations using chemical flocculants demonstrated promising results. Nevertheless, further research is required to determine the practical implementation methods in actual mining environments and to assess potential secondary impacts (Zhang et al., 2024).

3.2.2 Tailings discharge

In addition to plumes generated by seafloor mining activities, discharge plumes are produced by the return of excess water after the initial treatment and dewatering of the slurry by surface vessels, as well as during the transportation of the slurry from the mother ship to the transport barge (Rodríguez et al., 2021). During this mining process, backwater creates a plume of sediment, also known as tailings. Ore is produced by lifting systems from the sea floor to ships, where it is dehydrated, and consists of seawater with residual fine particles (< 10 μm) after centrifugation (Levin et al., 2016).

The tailings discharge process primarily involves releasing tailings slurry into seawater at different depths, a procedure that elevates the concentration of suspended solids and metal ions in the water (Ramirez-Llodra et al., 2015). These plumes may contain significantly less particulate matter than seafloor plumes; however, the particles could be so small that they are deposited more slowly and can travel greater distances, potentially reaching as far as 1,000 km, depending on the depth at which they are released and the temperature difference between the released water and the ambient conditions (Leung et al., 2020). They may have an impact on local mid-water ecosystems. The feeding of many gelatinous zooplankton in pelagic and bathyal regions may be affected by increased particle content (David, 2002). Effective control of surface operations is necessary to limit the introduction of nutrient-rich cold water at the surface, which has the potential to alter phytoplankton production and, consequently, surface water ecosystems (Weaver et al., 2018). Simultaneously, the presence of solid suspended particles and metal ions lowers the concentration of dissolved oxygen in seawater and influences the redox environment of the water changes (Dong et al., 2021).

Tailings discharge can also affect temperature. The temperature of the seafloor at water depths of 4,000 to 6,000 m is typically between 1 and 2°C, while the temperature of the tailings has been estimated to exceed 7°C. The impact of discharging tailings into seawater with a large temperature difference is incalculable (Prisetiahadi and Yanagi, 2008). At the same time, changes in temperature and salinity are always inseparable. Such changes often lead to transformation in the thermocline, especially in areas with shallower water depths (Dong et al., 2021).

3.3 Impact on the sea surface area

The environmental impacts of deep-sea mining primarily occur across two depth zones: one at the seafloor where mining vehicles operate, and another in the surface or upper ocean layers near the tailings discharge points. Mineral gathering processes, such as the upward transportation of minerals via pipeline and the transfer of minerals by production support vessels, all have potential impacts on the sea surface.

3.3.1 Pollutant emissions

Various pollutants will be formed during deep-sea mining, including accidental oil spills, chemical leaks, garbage dumping from mining vessels, species invasions (transport of animals, microorganisms, and viruses from the seafloor to water surface) accompanying mining operations, as well as emissions of carbon dioxide and sulfur dioxide. The discharged pollutants exhibit elevated concentrations of nutrients, suspended particulate matter, and trace metals compared to the surrounding surface waters. Their discharge not only alters the physicochemical environment in the marine areas surrounding the mining vessel but also impacts the upper oceanic ecosystem (Wang and Zhou, 2001).

3.3.2 Anthropogenic light

Surface support platforms introduce significant quantities of artificial light, which may influence ecological processes in the upper ocean, such as the vertical migration of some planktonic organisms organisms (Troy et al., 2013). Artificial lighting on boats at night can disorient birds. Once a bird enters a lighted area, it may become "trapped" and not leave that area, which may increase the probability of birds colliding with each other. Artificial night lights also attract many species, including squid and large predatory fish birds (Longcore and Rich, 2004).

3.3.3 Noise

Vessels operating at sea increase noise levels, and noise combined with vibration can affect the auditory systems of many fish and marine mammals by inducing behavioral changes, masking communication, and even causing temporary changes in hearing thresholds or permanent damage (Nedelec et al., 2017).

Surface vessels can be a major source of sound, generated by various factors, including propellers, engines, generators for dynamic positioning, hydraulic pumps, and noise related to the transfer of nodules to barges. Along with propeller and mechanical noise, there may be several high-intensity sound sources on board, such as echo sounders, ADCPs, Doppler logs, and acoustic pingers, which assist in the dynamic positioning of the ship and collector systems. Thus, the effects of continuous operation of ships must be evaluated (Weaver et al., 2018).

4 Environmental impact assessment, monitoring and management of deep-sea mining

4.1 Environmental impact assessment

According to customary international law and the United Nations Convention on the Law of the Sea (UNCLOS, Article 165 (2) d, f, h and 206), there exists a general obligation to conduct environmental impact assessments (EIAs) (Warner, 2012). However, the process and specific requirements for conducting an EIA in the context of deep-sea mining, particularly in areas beyond national jurisdiction, have not yet been fully developed. The draft EIA should be prepared during the resource assessment phase of the project, i.e., after exploration but before the commencement of mining activities (Durden et al., 2017). The EIA report should address the following key aspects:

1. Risk assessment of mining techniques, with particular attention to potential risks associated with plumes generated by the cutting head, noise produced by underwater operations, and the risks related to submarine mining vehicles and surface ships, including detection and response protocols (Clark et al., 2020).
2. The potential impacts on the composition, structure, and functioning of ecosystems (Van Dover et al., 2017).
3. Indirect effects of deep-sea mining, including ecotoxicity and the impacts of plumes on benthic fauna and the pelagic environment (Washburn et al., 2023).

4.2 Environmental monitoring plan

The environmental monitoring plan should outline the types of monitoring conducted at each stage of the project. The types of monitoring include (Collins et al., 2013):

1. Verification Monitoring: This should be conducted at the start of the project or activity and involves intensive, real-time, and comprehensive monitoring to verify the assumptions made during the environmental impact assessment phase. After the completion of the verification monitoring period, the project may transition to the compliance monitoring phase.
2. Compliance Monitoring: This should be carried out throughout the entire duration of the project to monitor the effectiveness of prescribed mitigation measures and assess whether these measures effectively reduce impacts to acceptable levels. Compliance monitoring should be used to ensure that specific environmental parameters are in line with applicable regulations, standards, guidelines, and contractual obligations.
3. Long-Term Monitoring: This should continue after the completion of the project. Long-term monitoring will partly extend the components of compliance monitoring, and its specifics will be determined based on the closure plan.

4.3 Management of environmental impacts from deep-sea mining

UNCLOS establishes a comprehensive legal structure with the overarching objective of harmonizing domestic and global maritime utilization while endeavoring to protect and preserve the marine environment. UNCLOS provides important provisions regarding deep-sea mining. Articles 136 and 137 explicitly outline the principle that deep-sea resources are the common heritage of mankind, ensuring the rational development and utilization of resources while safeguarding the equitable distribution of development rights and considering the interests of both present and future generations (Mestre et al., 2017). States are required to protect the marine environment and to take measures to prevent, reduce, and control pollution resulting from mining activities, thereby maintaining ecological balance (Lallier and Maes, 2016). Article 145 stipulates provisions for preventing, reducing, and controlling pollution and other hazards to the marine environment, as well as interference with the ecological balance of the marine environment, with particular emphasis on protection against harmful effects from activities such as drilling, dredging, and excavation (Singh and Hunter, 2019).

The International Seabed Authority, under the framework of the draft regulations for mineral resource development, has developed strategies for managing and mitigating the environmental impacts of deep-sea mining. These strategies aim to balance resource extraction with environmental protection to ensure the long-term sustainability of deep-sea ecosystems (Durden et al., 2018). The draft regulations for mineral resource development outline specific provisions for monitoring and management, introducing an adaptive management approach. Adaptive environmental management is an iterative method that tests the achievement of defined objectives and provides appropriate, reversible management interventions to further understand the resources being studied (Halfar and Fujita, 2002). The monitoring plan includes clear requirements regarding monitoring methods, parameters to be monitored, and monitoring stations. Additionally, the management of mining effluents and waste must comply with relevant regulations, guidelines, assessment reports, and conventions. Waste assessment and preventive auditing must evaluate compliance, prevention measures, and establish waste reduction goals. Strategic plans should be formulated and updated, considering the potential effects of waste management alternatives on the marine environment.

5 Conclusion and perspectives

5.1 Conclusion

Deep-sea mining, as an emerging resource exploitation method addressing the growing global resource demands, holds substantial economic potential. However, its environmental implications cannot be overlooked. The potential environmental impacts of deep-sea mining have become a central point of contention among scientists and policymakers. Current research indicates that deep-sea mining activities may cause irreversible damage to vulnerable deep-sea ecosystems, with complex impact mechanisms spanning significant temporal and spatial scales.

This review provides a brief overview of major seabed mineral resources and their extraction systems, followed by a detailed examination of the direct and indirect environmental impacts of deep-sea mining. These impacts include destruction of deep-sea organisms and their habitats, underwater noise propagation, and the formation of sediment plumes. Particular attention is given to various plume formation mechanisms and their potential threats.

This review also suggests directions for mitigating or resolving environmental impacts during actual mining operations, such as improving mining systems, optimizing mining vehicle design parameters, and using flocculants to accelerate plume settlement. However, significant limitations persist, notably the severe lack of baseline data on deep-sea ecosystems (including species distribution, biomass, and functional diversity), making it challenging to accurately assess the temporal and spatial scope of mining impacts.

5.2 Perspectives

1. Currently, there is no comprehensive, commercially viable model for the development of marine mineral resources worldwide. Achieving sustainable development of marine mineral resources is an important issue that requires further research. To achieve sustainable deep-sea resource development, it is essential to strike a balance between deep-sea mining and environmental protection.
2. Deep-sea mining activities have both direct and indirect impacts on the marine environment, including destruction of deep-sea organisms and their habitats, noise propagation in seawater, and the formation of sediment plumes. Predicting migration mechanisms and controlling the spread of large-scale plumes remain critical issues that need to be addressed through physical experiments, numerical simulations, and field monitoring.
3. To better understand the spatiotemporal evolution of resuspended sediments during mineral extraction, reliable *in-situ* observation technologies are necessary. In the future, establishing models will require a substantial amount of field monitoring data. This will enable the quantitative assessment of the environmental impacts of deep-sea mining based on sediment migration and dispersion.

Author contributions

CT: Formal analysis, Investigation, Writing – original draft. WY: Writing – review & editing, Conceptualization, Resources. YT: Writing – review & editing, Formal analysis. FD: Software, Writing – review & editing. XD: Writing – review & editing, Resources. PG: Writing – review & editing, Conceptualization, Supervision. WZ: Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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