

## Review

# Deep-Sea Mining and the Sustainability Paradox: Pathways to Balance Critical Material Demands and Ocean Conservation

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## Abstract

Deep-sea mining presents a critical sustainability paradox; it offers access to essential minerals for the technologies of the green transition (e.g., batteries, wind turbines, electric vehicles) yet threatens fragile marine ecosystems. As the terrestrial sources of these materials face mounting geopolitical, environmental, and ethical constraints, undersea deposits are increasingly being viewed as alternatives. However, the extraction technologies remain unproven at large scales, posing risks related to biodiversity loss, sediment disruption, and altered oceanic carbon cycles. This paper explores how deep-sea mining might be reconciled with sustainable development, arguing that its viability hinges on addressing five interdependent challenges—technological readiness, environmental protection, economic feasibility, robust governance, and social acceptability. Progress requires parallel advancements across all domains. This paper reviews the current knowledge of deep-sea resources and extraction methods, analyzes the ecological and sociopolitical risks, and proposes systemic solutions, including the implementation of stringent regulatory frameworks, technological innovation, responsible terrestrial sourcing, and circular economy strategies. A precautionary and integrated approach is emphasized to ensure that the securing of critical minerals does not compromise marine ecosystem health or long-term sustainability objectives.

**Keywords:** circular economy; critical materials; deep-sea mining; green transition; marine ecosystem conservation; polymetallic nodules; sustainable resource management



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## 1. Introduction

Sustainable development is essential for the long-term prosperity and health of humanity and our planet. It involves balancing economic growth, environmental stewardship, and social equity to meet the current needs without compromising the ability of future generations to meet theirs [1]. By adopting sustainable practices—such as conserving natural resources, reducing pollution, and transitioning to renewable energy—societies can combat climate change, protect ecosystems, and enhance human health and livelihoods. Furthermore, sustainable development encourages efficient resource management and the advancement of green technologies, fostering a resilient and equitable future.

The pursuit of sustainable development is closely linked to the availability and effective management of a wide range of raw materials. These include lithium, cobalt, and nickel, which are essential for the production of batteries, such as lithium ion, nickel–cobalt–aluminum, and nickel–manganese–cobalt batteries, used predominantly in electric vehicles, as well as other electric energy storage systems [2,3]. Copper, due to its high electrical and thermal conductivity, low resistivity, durability, and flexibility, is indispensable for wiring

and various components in almost all electrical equipment. Rare earth metals are crucial for enhancing the magnetic properties of permanent magnets, which are key components in electrical machines used in renewable energy conversion and electric vehicles [4,5]. Additionally, graphite plays a vital role in battery anodes, while platinum group metals (such as platinum, palladium, rhodium, and iridium) are important for use in catalytic converters and hydrogen fuel cells.

These raw materials, with their unique physical and chemical properties, are vital to numerous industries and technologies. Due to their substantial economic importance, they are officially classified as critical or strategic materials.

Industrialized nations have developed lists of critical and strategic materials to guide policies on resource management, trade, and national security [6]. These lists are frequently revised, with a focus on the economic relevance of materials for emerging technologies, as well as potential supply disruptions and dependence on foreign sources [7]. For instance, the USA regularly updates its list of critical minerals, managed by the U.S. Geological Survey (USGS) under the Department of the Interior. The most recent list, released in 2022, includes 50 minerals [8]. Similarly, the European Union has established a list of strategic and critical raw materials, with the latest edition being published in 2023. This fifth version includes 16 strategic and 34 critical materials and material groups [9]. While the terms “critical” and “strategic” materials are often used interchangeably, there exists only a subtle, nuanced difference in their usage, as their designating criteria may overlap [10].

These critical materials are increasingly vulnerable to supply chain disruptions due to limited sources, geopolitical tensions, and market monopolization [6]. The demand for them continues to surge as societies transition to renewable energy and electric mobility [11–13]. To address shortages, policy-makers and industries are exploring legislative, technical, and circular economy strategies [14].

Policy tools such as stockpiling and extended producer responsibility laws require global coordination and funding, while reshoring production demands costly infrastructure investments. Technical solutions, such as substituting critical materials or improving material efficiency efforts, face challenges such as high costs and performance trade-offs.

Recycling and circular economy practices offer the most promise but are hindered by technical complexity in material separation, low collection rates, inconsistent regulations, and non-recyclable product designs [14]. Despite significant efforts to increase the share of recycled raw materials, this approach alone is insufficient to meet the growing demand, as the supply of recovered materials is inherently limited by the quantity that is originally mined [12].

Traditional mining, therefore, remains essential, despite its considerable drawbacks, such as environmental degradation (habitat destruction, pollution, and carbon emissions), worker health risks, community displacement, and long-term land contamination. To mitigate these impacts, sustainable practices must be implemented in this sector. Advanced technologies, such as automation and water recycling, can improve waste management efforts and ensure safer storage of tailings. Additionally, strengthening regulations, promoting ecosystem restoration, and encouraging responsible resource extraction are crucial steps. Reducing the carbon footprint of the mining sector will require greater reliance on renewable energy, increased investment in green mining R&D, and closer industry collaboration.

However, in the long term, the goals of sustainable development (particularly the clean energy and green transportation transition and digital transformation goals) cannot be met without expanding the supply base beyond terrestrial sources.

In this context, deep-sea mining emerges not just as an alternative but as a strategic necessity. While it must be approached with strict environmental safeguards, its potential

to unlock vast reserves of critical metals makes it indispensable for closing the looming supply–demand gap sustainably. Emerging solutions (most notably the responsible exploitation of deep-sea mineral resources) are, therefore, being explored to diversify supply sources without exacerbating the ecological and social harms historically associated with mining [15].

While the exploration of terrestrial reserves of critical materials is severely limited, deep-sea mining presents a promising alternative, since it reduces the dependence on environmentally damaging land-based mining and plays a significant role in advancing sustainable development [16].

Deep-sea polymetallic nodules present a promising alternative source of critical raw materials essential for sustainable development. These nodules are abundant on the ocean floor and contain high concentrations of critical raw metals such as cobalt, nickel, and manganese. However, their extraction raises significant technological hurdles, economic feasibility concerns, regulatory and legal barriers, environmental risks, and social opposition.

This tension gives rise to a sustainability paradox; namely, the conflict between securing minerals urgently needed to decarbonize economies, transition to renewable energy systems, and support green technologies and the imperative to avoid irreparable harm to marine ecosystems through deep-sea mining. At its core, this paradox highlights a critical dilemma. The global push for green technologies requires vast quantities of metals that are scarce, geopolitically contested, or ethically problematic to mine on land. While deep-sea mining is proposed as a solution to these shortages, it threatens fragile marine ecosystems that serve as biodiversity hotspots, carbon sinks, and regulators of planetary processes such as nutrient cycling and climate stability. The contrary nature lies in the fact that addressing one existential crisis (climate change) risks exacerbating another (ocean degradation), thereby undermining the broader goal of sustainability. This paper explicitly interrogates the paradox through five interconnected critical lenses—technology, environment, economy, policy, and society—to ensure that progress in any individual domain is not evaluated in isolation but rather concerning its influence on and dependence upon the others. These dimensions are deeply interwoven; for example, technological advances must be accompanied by stringent environmental safeguards, economically viable models require strong policy and governance structures, and public acceptance hinges on transparent processes and equitable benefit-sharing. Only by addressing all five domains in parallel can sustainable pathways for deep-sea mining be credibly identified. This integrated assessment is essential to move beyond narrow cost–benefit calculations and toward a systems-level understanding of sustainability.

Resolving this paradox demands balancing immediate material needs with long-term ecological stewardship. For instance, deep-sea ecosystems, which take millennia to recover, face destruction just as the world races to meet net-zero emissions targets by 2050. Additionally, exploiting the ocean floor, a resource deemed the common heritage of humankind, for short-term gain challenges intergenerational equity goals. Therefore, systemic solutions are essential, including reducing demand through recycling, material substitution, and efficient resource use; enforcing robust environmental safeguards and establishing marine protected areas; and prioritizing research to fully understand ecological risks before scaling operations. Equally important are transparent economic assessments that incorporate externalities and inclusive decision-making processes that respect the rights and voices of coastal and Indigenous communities.

Consequently, deep-sea mining can only align with sustainability goals if rigorous environmental protection, technological innovation, and comprehensive regulatory frameworks are implemented. These frameworks must also embed equitable benefit-sharing mechanisms to guarantee that economic gains do not accrue at the expense of vulnerable

stakeholders or irreplaceable ecosystems. These measures must ensure that economic benefits do not come at the expense of irreparable harm to the least-understood ecosystems on Earth, thereby preserving their role in global ecological health.

While the prior literature has addressed the technological, environmental, and regulatory challenges of deep-sea mining, this paper uniquely frames these tensions as a sustainability paradox intrinsic to the imperative of the green transition. It contributes a novel framework that analyzes this paradox through five interdependent dimensions (technology, environment, economy, governance, and society), which must progress synergistically to enable viable and responsible operations. To our knowledge, no existing study structurally integrates these dimensions as mutually reinforcing pillars or positions their systemic interrelations as the foundation for sustainable decision-making in the context of deep-sea mining.

Against this background, this paper aims to contribute, however modestly, to the understanding of sustainable development by evaluating the role of deep-sea raw material resources. It provides an overview of undersea mineral deposits, highlighting their composition, distribution, and potential advantages over land-based resources. Section 3 explores the current and emerging deep-sea mining technologies, including nodule collection systems, vertical transport methods, surface processing techniques, environmental monitoring tools, and alternative approaches that may mitigate the ecological impacts. The next section examines the key challenges and limitations of deep-sea mining. In Section 5, potential pathways for resolving the sustainability paradox are presented, focusing on prioritizing land-based alternatives, enforcing strict environmental protection strategies, advancing mining technologies, strengthening governance frameworks, and applying a precautionary scientific approach. Finally, the conclusions summarize the findings and emphasize the need for a balanced, responsible strategy that integrates deep-sea resource utilization with ocean conservation and sustainable development objectives.

## 2. Undersea Mineral Deposits

Oceans and seas cover approximately 70% of the Earth's surface. This vast expanse not only plays a critical role in regulating the climate on our planet and supporting marine ecosystems but also provides a wide array of resources essential for human survival and development. For centuries, fisheries have been a vital source of food globally. In recent decades, renewable energy sources from the oceans, such as wind, wave, and tidal energy, have been extensively harnessed. However, the seabed holds great potential in the form of mineral resources, including many critical materials crucial for sustainable development. Among these mineral resources are polymetallic nodules, polymetallic sulfides, and cobalt-rich ferromanganese crusts.

### 2.1. Polymetallic Nodules

Polymetallic nodules are mineral-rich, potato-shaped concretions (see Figure 1) that form over millions of years on the ocean floor through the slow precipitation of metals from seawater and sediment pore water. These nodules are composed predominantly of manganese (25–30%) and iron (10–15%), along with economically significant concentrations of nickel (~1.3%), copper (~1.1%), and cobalt (~0.2–0.3%) [17,18]. They also contain trace amounts of rare earth elements, molybdenum, lithium, and other critical raw materials essential for green technologies, such as electric vehicle batteries, wind turbines, and renewable energy conversion systems [19].



**Figure 1.** Manganese nodules [20].

Unlike conventional land-based ores, polymetallic nodules often exhibit low levels of toxic heavy elements such as arsenic, cadmium, and mercury, making them attractive from an environmental processing standpoint. Recent technological advancements suggest that the bulk of these nodules can be processed with minimal waste generation, supporting the concept of near-zero waste metallurgy [21].

These nodules are found on abyssal plains at depths ranging from 4000 to 6000 m, typically lying loose on or just below the sediment surface. Despite widely varying estimates, it is universally acknowledged that the Clarion–Clipperton Zone (CCZ), located in the northeastern Pacific Ocean between Hawaii and Mexico, is the most prominent and extensively studied nodule deposit area. Spanning over 4.5 million km<sup>2</sup>, the CCZ contains approximately 21–22 dry Gt of polymetallic nodules, from which an estimated 260 Mt of nickel, 230 Mt of copper, 44 Mt of cobalt, and a substantial quantity (around 6 Gt) of manganese could potentially be extracted [17,22]. Based on this estimate, the tonnages of many critical metals in the CCZ nodules are greater than those found in global terrestrial reserves [23]. Almost all of these metals are on the list of critical or strategic raw materials [24,25].

Other notable regions with nodule occurrences include the Central Indian Ocean Basin (CIOB), the Peru Basin, and the Cook Islands Exclusive Economic Zone (EEZ) in the South Pacific [26]. Each of these areas hosts nodules with varying metal contents and morphologies, influenced by local sedimentation rates, geochemistry, and biological activity [24,27].

## 2.2. Polymetallic Sulfides

Polymetallic sulfides are geological formations found on the ocean floor (see Figure 2), particularly around hydrothermal vent systems. These deposits are rich in valuable metals such as copper, zinc, gold, and silver, often with higher metal grades than polymetallic nodules.

They are formed when mineral-rich fluids, heated by the mantle of the Earth, and are expelled through hydrothermal vents. As these hot fluids mix with cold seawater, metals precipitate and accumulate on the seabed, creating substantial deposits of sulfur compounds and various metals. Polymetallic sulfide deposits are primarily located along mid-ocean ridges, back-arc basins, and submarine volcanic arcs, with notable examples including the East Pacific Rise, Galapagos Rift, and the Southwest Indian Ridge.

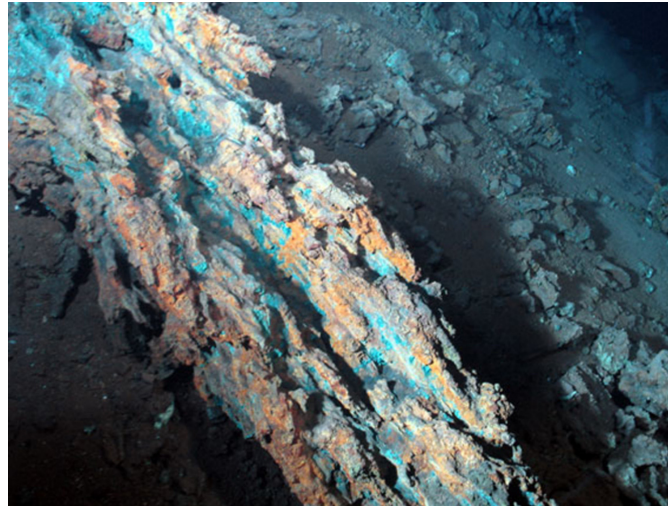


**Figure 2.** Hydrothermally formed copper sulfides on the seabed [28].

### 2.3. Metal-Rich Crusts

Another significant type of deep-sea mineral deposit comprises metal-rich crusts, particularly cobalt-rich ferromanganese crusts. These crusts develop over tens of millions of years through the extremely slow precipitation of metal oxides from seawater onto the hard rock surfaces of underwater seamounts, plateaus, and ridges. As these metal compounds accumulate, they form hard, consolidated layers rich in iron and manganese oxides, which also incorporate economically important metals such as cobalt, nickel, copper, molybdenum, tellurium, platinum group elements, and rare earth elements [29].

Cobalt-rich crusts can contain up to 2% cobalt by weight, along with notable concentrations of nickel (0.3–0.8%), platinum (up to 4 ppm), and rare earth metals. These grades often surpass those of terrestrial ores currently being mined [30]. Such crusts are most abundant in the Pacific Ocean, particularly in the northwestern and central regions, including the Hawaiian Archipelago, the Marshall Islands, and the Magellan Seamount cluster [31,32].

Despite these challenges, cobalt-rich crusts have attracted increasing attention due to their relatively shallow deposits, high concentrations of strategic metals (including high-grade cobalt and rare earth elements), and widespread distribution, all of which make them promising targets for future extraction efforts [32].

### 2.4. Comparison of Deep-Sea Mineral Deposit Mining

Among the above-mentioned types of deep-sea mineral resources, each offers a distinct combination regarding the geological setting, metal content, extraction challenges, and environmental implications.

Polymetallic nodules are particularly attractive due to the co-location of several economically valuable metals within a single deposit. These nodules rest loosely on or just beneath the soft sediments of the abyssal plains, allowing for their collection without drilling or blasting. In contrast, polymetallic sulfides form solid chimneys and mounds on rugged seafloor terrain, requiring mechanical cutting and posing a risk of releasing acidic leachates harmful to local marine ecosystems. Cobalt-rich ferromanganese crusts, which are strongly bonded to the rocky flanks of underwater mountains, also necessitate advanced seafloor cutting or fragmentation technologies.

Depth also differentiates these deposits. While polymetallic nodules are typically located at great depths of 4000 to 6000 m, polymetallic sulfides are found at 1000 to 3500 m and cobalt-rich crusts occur in even shallower areas, ranging between 800 and 2500 m [29].

While all forms of deep-sea mining carry ecological risks, the relative predictability and uniformity of nodule fields, along with recent advancements in environmental monitoring and sediment plume control, seem to make the management of the impacts more tractable compared to the more ecologically sensitive and topographically complex sulfide and crust sites [33].

This paper prioritizes polymetallic nodule mining not for its technical attributes but as a critical case study to interrogate the “sustainability paradox”; namely, the competing imperative for critical materials enabling sustainable development versus environmental, economic, and governance pressures driving irreconcilable tensions in deep-sea mining policy and practice.

### 3. Deep-Sea Mining Technologies

The deep-sea mining of polymetallic nodules requires specialized technologies to operate in extreme oceanic conditions (high pressures, low temperatures, and complete darkness) while minimizing the environmental impact. The key technologies involved can be categorized into nodule collection systems (e.g., crawler-based collector, suction dredging, and bucket ladder systems), vertical transport mechanisms (e.g., hydraulic pumping, air lift, and mechanical conveyor systems), and surface processing solutions (e.g., onboard sorting and dehydration units). Additionally, environmental monitoring technologies such as autonomous underwater vehicles (AUVs) and sediment plume modeling can help assess the ecological impacts. Emerging approaches, including the use of robotic harvesters, electromagnetic collection, and biomining, offer alternative methods for sustainable extraction. This section provides a detailed overview of these deep-sea mining technologies [34].

#### 3.1. Nodule Collection Technologies

Over the past few decades, various deep-sea mineral collection technologies have been explored, including the submarine drag bucket system, continuous line bucket system, and shuttle vessel mining system. The submarine drag bucket system utilizes a series of buckets dragged along the seafloor to collect nodules, although it causes significant sediment disruption and seafloor scarring. The continuous line bucket system, which operates with a continuous loop of buckets lifting nodules to the surface, shows improved efficiency but struggles with issues related to high operational complexity, mechanical wear, and significant energy consumption. The shuttle vessel system, where a collector gathers nodules and transfers them to a surface vessel via shuttling units, reduces the need for continuous lifting but suffers from limited scalability and logistical inefficiencies [35].

##### 3.1.1. Crawler-Based Systems for Nodule Collection

Crawler-based nodule collection systems (see Figure 3) are the most widely proposed and promising technologies for the deep-sea mining of polymetallic nodules.

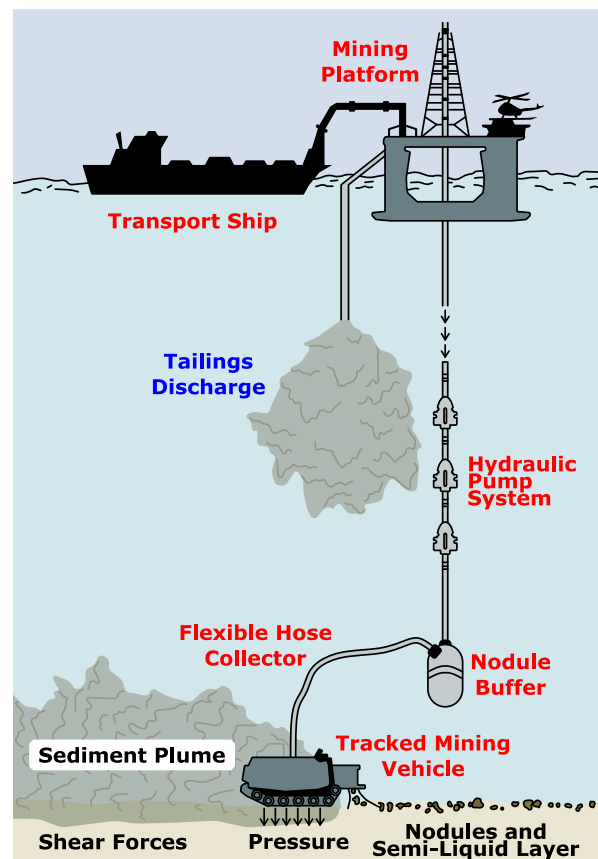


**Figure 3.** Remotely operated crawler equipped with a hydraulic pumping system [36].

Their main part is an autonomous or remotely operated undersea vehicle designed to move across the deep-sea floor, collecting polymetallic nodules while minimizing environmental disturbance. The tracked or wheeled vehicle (such as the collector designed by the Allseas Group S.A. (Châtel-Saint-Denis, Switzerland), pictured in Figure 4 [37]) can intelligently navigate on the soft and uneven seabed, using sensors and cameras to map the terrain and optimize its movement.



**Figure 4.** Underwater deployment of the Allseas-designed pilot nodule collector [38].

The collection mechanism can be either hydraulic or mechanical. Hydraulic systems employ water jets or suction pumps (utilizing suck-up collection or Coandă-effect-based

technology, as shown in Figure 5) to lift the nodules, while mechanical collectors use rotating drums, conveyor belts, or rakes to scoop them up [39].

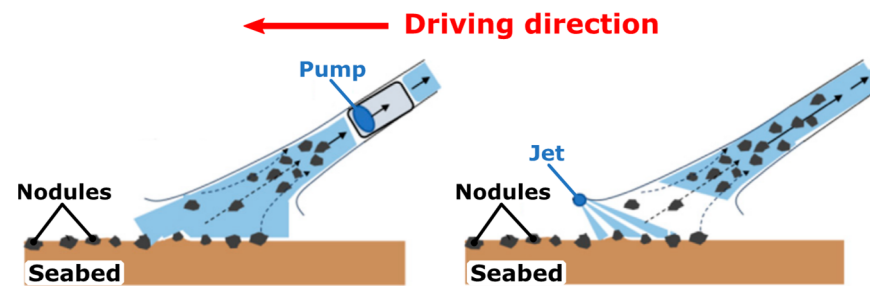


Figure 5. Hydraulic nodule collection heads—suction and Coandă types [35].

Once gathered, the nodules are separated from excess sediment through onboard screening systems, ensuring efficient material collection while controlling the sediment dispersion. The nodules are then stored in a buffer system, allowing continuous collection while synchronizing with the vertical transport system [40]. To mitigate the environmental impact, these systems incorporate sediment plume management strategies, such as controlled water jet propulsion or shielding mechanisms, reducing the disruption of marine ecosystems [41]. Finally, the collected nodules are transferred to the surface vessel via hydraulic pumping or air lift transport, where they are further processed and stored [37].

A great variety of deep-sea mining equipment systems have been extensively studied and developed by various research institutions, mining companies, and international organizations as part of pilot projects and prototype testing. These systems offer a practical solution for large-scale nodule harvesting, as they can operate continuously on the seabed with minimal human intervention. Several deep-sea mining trials have successfully demonstrated the feasibility of crawler-based approaches [42,43].

However, these technologies are only at an experimental level, with no series-manufactured devices available globally, relying instead on custom-built prototypes for ongoing research and pilot projects. Despite their potential to play a critical role in future seabed resource extraction, significant concerns persist regarding their large-scale use (detailed in Section 4), highlighting the need for further research, technological refinement, and regulatory development before widespread deployment.

### 3.1.2. Design Targets for Nodule Collection Systems

The design of a nodule collection system must balance the production capacity, efficiency, and environmental sustainability. A key factor is the pickup efficiency, which measures the proportion of nodules successfully collected from a given area. Maximizing this efficiency ensures optimal resource recovery. The production capacity must also meet economic viability requirements, typically requiring annual yields ranging between 2.8 and 3.0 million tons of dry nodules [44].

The water flow is another crucial consideration, as both hydraulic and mechanical collection methods rely on it for pick-up and separation. However, excessive water flow can increase sediment plumes, making its minimization essential for reducing the environmental impact. The environmental concerns extend beyond turbidity to include seafloor disturbance and noise generation, both of which must be minimized to protect fragile deep-sea ecosystems.

Seafloor interactions must be carefully managed to prevent clogging and excessive soil collection, ensuring smooth operation. The reliability of the system is also a priority, favoring designs with fewer active components to reduce the risk of failure and downtime. Additionally, longevity is a key factor, requiring high-wear-resistant materials to extend

the system's operational lifespan. By considering these design principles, nodule collection systems can facilitate efficient and sustainable deep-sea mining operations [44].

### 3.2. Vertical Transport Systems

Several transport technologies have also been proposed for lifting polymetallic nodules from the seafloor to the surface, each with distinct advantages and limitations. The oldest approach, involving mechanical conveyor systems (such as belt or bucket conveyors), offers controlled and predictable transport with relatively lower energy consumption rates. However, the mechanical complexity increases the risk of failure in the harsh deep-sea environment. Air lift systems, which inject compressed air into the pipeline to create a pressure differential, provide an energy-efficient alternative. Nevertheless, they are limited by depth constraints and require precise control during air injection.

More advanced technology options involve hydraulic pumping systems, which utilize high-pressure water flow to transport nodules through pipelines. These systems allow for continuous operation and high transport capacity levels, making them reliable and scalable for handling large volumes of nodules with fewer moving parts, thereby reducing the maintenance concerns in deep-sea operations. They also have some drawbacks, as they require significant energy inputs and can potentially generate significant sediment plumes.

### 3.3. Surface Processing and Handling

Surface processing and handling play a crucial role in ensuring the efficiency and sustainability of deep-sea nodule mining operations. Once the nodules reach the surface, onboard sorting and processing systems separate them from excess sediment, reducing unnecessary material transport and optimizing storage efforts. These facilities may include vibrating screens, hydrocyclones, or gravity-based separation methods to clean and classify the nodules before further handling.

Additionally, desalination and dehydration units remove excess seawater from the collected nodules, significantly improving the transport efficiency by reducing the mass and volume. This step not only minimizes the energy required for shipping but also mitigates the release of potentially harmful seawater discharge, lowering the environmental impact. By integrating these processing techniques onboard mining vessels, the operational efficiency is enhanced while ensuring compliance with environmental standards [45].

### 3.4. Environmental Monitoring Technologies

Environmental monitoring is crucial in deep-sea mining to assess and mitigate the impacts on marine ecosystems. AUVs play a vital role by allowing the real-time monitoring of seabed conditions and ecosystem interactions. Equipped with sensors and high-definition cameras, AUVs can operate continuously, collecting data on the water quality, sediment composition, and biological activity, thereby offering comprehensive insights into the environmental effects of mining activities [46,47].

Sediment plume modeling and mitigation are essential for predicting and managing the dispersal of particles disturbed during mining operations. Advanced computational models simulate the plume behavior, enabling the development of strategies to minimize the ecological disturbances. These models guide the design of monitoring programs and inform the implementation of effective mitigation measures to protect marine life from the adverse effects of sedimentation [48,49].

Biodiversity assessment tools, including AI-powered cameras and sensors, are employed to monitor marine life interactions with mining activities. These technologies facilitate the tracking of species presence, behavior, and habitat use information, providing data essential for evaluating the impacts of mining and informing conservation efforts. The

integration of AI enhances the accuracy and efficiency of data analyses, supporting the development of strategies to preserve marine biodiversity in the face of industrial activities.

Implementing these environmental monitoring technologies ensures that deep-sea mining operations are conducted responsibly, with a focus on minimizing the harm to ocean ecosystems and promoting sustainable resource extraction.

### 3.5. Alternative Mining Approaches

As the concerns over the environmental impacts of traditional deep-sea mining methods continue to rise (see Section 4.2), alternative approaches are being explored for enhanced selectivity, to reduce sediment plumes, and to minimize the harm to marine ecosystems.

One such approach involves robotic harvesters, which utilize AI-driven robotic arms to selectively pick up polymetallic nodules while leaving the sediment and fragile marine life undisturbed [50]. These systems leverage advanced computer vision and machine learning technologies to identify and extract nodules efficiently. While robotic harvesters significantly reduce the environmental disturbance and prevent excessive seabed disruption, they face challenges related to their slower collection rates, high operational costs, and complex maintenance requirements. Currently, these systems have reached a medium level of technological readiness, with prototypes successfully tested in controlled environments, although their large-scale deployment remains in its early stages [51]. Future advancements in AI, robotics, and real-time adaptive decision-making could further improve their efficiency and enable autonomous operations with minimal ecological impact.

While deep-sea generally mining relies on mechanical dredging systems that physically scrape the seabed, two non-contact extraction methods have emerged as promising alternatives—electromagnetic harvesting and microwave- or radiofrequency-assisted collection. These approaches leverage the intrinsic physical properties of polymetallic nodules to enable selective recovery with minimal disturbance to the seabed.

Electromagnetic harvesting exploits the electrical conductivity of metal-rich nodules. A pulsed electromagnetic field induces eddy currents within the nodules, generating a repulsive Lorentz force that detaches them from surrounding sediments without direct contact. This non-invasive technique shows high efficiency in nodule recovery and results in significantly reduced sediment plume formation. However, its performance declines in highly conductive clay sediments and when targeting nodules with low iron contents. In contrast, microwave- or radiofrequency-assisted collection targets the dielectric properties of the nodules. Rapidly heating hydrated metal oxides induces thermal fracturing at the nodule–sediment interface, enabling easy detachment. This method is also effective in clay-rich environments where electromagnetic harvesting underperforms. Nevertheless, it requires thermal buffer zones to minimize heat transfer and protect sessile benthic fauna [52].

These non-contact technologies do not eliminate the environmental impacts but offer the potential to significantly reduce them. Despite their promise, both methods remain at low to medium levels of technology readiness. Experimental studies have demonstrated their feasibility, although their large-scale implementation is still lacking [17,53]. Continued research and development are essential to improve their technical performance and assess the long-term ecological implications, ultimately enhancing their viability for future deployment.

Biomining presents a transformative approach to deep-sea mineral extraction by harnessing microbial bioleaching to recover valuable metals from seabed deposits [54]. This method employs extremophilic microorganisms (such as *Acidithiobacillus* or *Leptospirillum* species) that thrive in extreme undersea conditions and catalyze the oxidation of iron and sulfur compounds in ores, releasing soluble metal ions (e.g., copper, zinc) into the solution

for recovery [55,56]. Biomining can be implemented in situ (directly on the ocean floor, where microbes interact with mineral-rich deposits under natural conditions) or ex situ (where extracted materials are processed in controlled bioreactors aboard ships or on land).

Compared to conventional deep-sea mining, biomining offers significant environmental advantages, as it minimizes the mechanical disturbance of seafloor habitats, reduces sediment plumes, and avoids the use of harsh chemicals. Furthermore, microbial systems can be engineered for targeted metal recovery, enhancing both the specificity and efficiency. Advances in synthetic biology and bioprocess engineering hold promise for scaling these systems to commercial viability while mitigating the ecological impacts.

While biomining has been extensively researched and applied in terrestrial mining operations, particularly for low-grade ores, its feasibility for deep-sea mining remains largely experimental. The extreme conditions of the deep ocean (high pressure, low temperature, and the absence of easily controllable bioreactor conditions) make large-scale bioleaching challenging. Additionally, slow metal extraction rates, the need for highly controlled conditions, and difficulties in scaling the process for industrial applications further hinder its practical implementation.

Currently, biomining remains at a low technology readiness level, with only a few pilot studies assessing its feasibility for deep-sea mining. Advances in bioengineering and synthetic biology could optimize microbial strains for enhanced extraction efficiency, potentially making biomining a viable, sustainable alternative to traditional metallurgical techniques. However, the lack of field studies and the technological scalability issues mean that commercial deep-sea biomining is not yet a realistic option. Future research is needed to develop specialized microbial strains capable of functioning under deep-sea conditions and to evaluate the environmental risks associated with bioleaching in marine ecosystems.

## 4. Challenges and Limitations of Deep-Sea Mining

As can be seen, deep-sea mining faces several significant barriers and limitations, encompassing technological, environmental, economic, and regulatory challenges.

### 4.1. Technological Challenges

The technological challenges of deep-sea mining stem from the extreme conditions of the ocean floor and the complexity of developing reliable, efficient, and environmentally sustainable extraction systems. Operating at depths often exceeding 5000 m requires specialized equipment capable of withstanding immense pressure and low temperatures while maintaining functionality over extended periods [18]. The current mining technologies, as detailed in Section 3, face significant engineering hurdles, including wear and tear due to abrasive sediments, potential clogging of hydraulic and pumping systems, and difficulties in real-time monitoring and control [57].

Another major challenge relates to the power supply and energy efficiency, as deep-sea mining operations require substantial energy, often relying on surface vessels to generate and transmit power to sub-sea machinery, which introduces additional logistical constraints [58]. Autonomous and remotely operated systems must also integrate advanced navigation, sensing, and communication technologies to function effectively in the deep-sea environment, where real-time data transmission is hindered by water-induced signal attenuation [59]. Furthermore, material selection processes for mining equipment must consider corrosion resistance due to prolonged exposure to seawater, adding to complexity to the design and manufacturing process. Addressing these technological challenges will require advancements in robotics, materials science, and energy-efficient extraction methods to enable deep-sea mining operations that are both economically viable and environmentally responsible [60].

#### 4.2. Environmental Concerns

The environmental concerns surrounding deep-sea mining are among the most urgent planetary challenges, with habitat destruction posing a primary threat. The seabed, part of the “Common Heritage of Mankind”, hosts an immense reservoir of biodiversity, with an estimated one million oceanic species, most still undiscovered (see Figure 6).



**Figure 6.** Deep-sea animals [61,62].

Mining operations risk irreversibly damaging these fragile ecosystems, potentially driving the extinction of endemic species and disrupting critical planetary processes, such as climate regulation, fisheries productivity, and elemental cycling [63]. These impacts not only threaten ecological stability but also undermine the intrinsic value of deep seas as a shared global legacy for future generations.

Another major environment-related issue is the generation of sediment plumes, caused by seabed disturbances and the discharge of fine particles into the water column during processing. These plumes can spread over vast areas, smothering marine life, reducing light penetration essential for photosynthesis, and degrading the water quality (as can be seen in Figure 7) [64,65]. Such disruptions threaten filter feeders and other species that struggle to adapt [66].

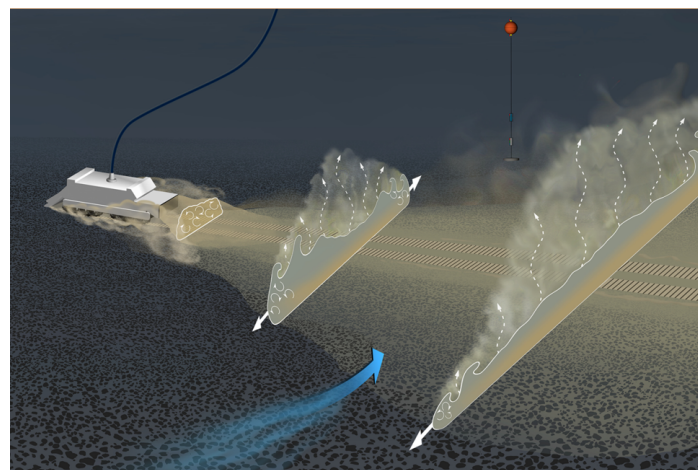


**Figure 7.** Sediment plume spreading behind a nodule collector vehicle [65].

The noise and vibrations generated by deep-sea mining equipment, remotely operated vehicles, and surface vessels pose further risks to marine ecosystems, particularly species reliant on low-frequency sounds for communication, navigation, and hunting (see Figure 8) [67].

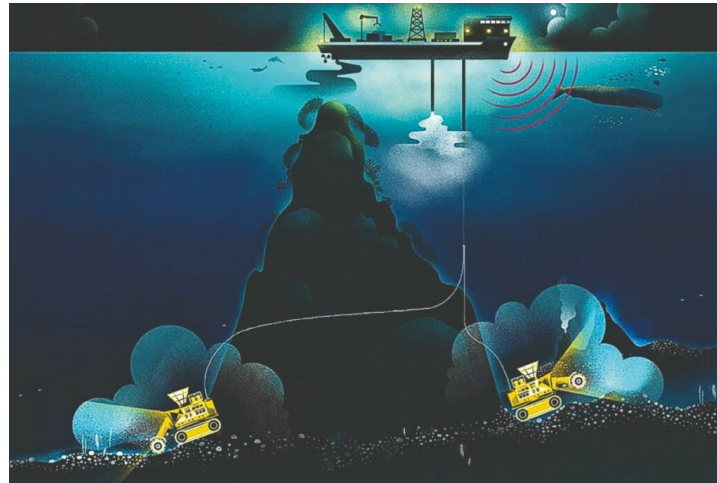


**Figure 8.** Impacts of deep-sea mining activities on marine wildlife and ecosystems [67].

Marine mammals, such as whales, are especially vulnerable, as mining noise can interfere with their acoustic signals, leading to disorientation, strandings, and disrupted migratory patterns. Moreover, continuous noise pollution induces chronic stress, alters feeding and mating behaviors, and disrupts predator–prey dynamics, further destabilizing marine ecosystems [68].

Chemical pollution is one of the most critical environmental risks related to deep-sea mining. Even the small quantities of toxic heavy metals (e.g., mercury, lead, cadmium) released during polymetallic nodule extraction can accumulate in marine organisms, bioaccumulating through the food web and threatening both biodiversity and commercially important fish populations. Such contamination also poses serious risks to human health via seafood consumption [69,70]. Additionally, mining activities disturb deep-sea sediments that have trapped harmful substances for millions of years, mobilizing these toxins and allowing ocean currents to spread them beyond the mining sites.

It appears that not all environmental impacts of deep-sea mining are already known. Recent research suggests that polymetallic nodules on the ocean floor may act as natural so-called geo-batteries, influencing deep-sea oxygen dynamics by facilitating electron transfer processes. Their removal could potentially disrupt anaerobic ecosystems that rely on these mechanisms for biochemical balance [71,72].

Deep-sea mining could also amplify existing human-induced stressors, such as climate change, pollution, and bottom trawling, leading to unpredictable ecological consequences. For example, disturbing the seabed may release stored carbon, potentially accelerating climate change.

The cumulative impact of these environmental disturbances remains highly uncertain due to the limited baseline data on deep-sea biodiversity and ecosystem functions. Unlike terrestrial ecosystems, which may recover over decades, deep-sea environments regenerate at an extremely slow pace due to their unique biological and geological processes [73]. Many deep-sea species have long lifespans and low reproduction rates, making ecosystem recovery efforts particularly difficult.

Further research and comprehensive international regulatory frameworks are urgently needed to fully understand the environmental consequences of deep-sea mining and to develop effective mitigation strategies. Unfortunately, the risks associated with these practices, particularly biodiversity loss and ecosystem disruption, are still underrecognized, even among industry and scientific experts [74]. Raising awareness and integrating scientific insights into global policies are essential steps toward safeguarding marine ecosystems and ensuring sustainable resource management [75].

#### 4.3. Economic Viability

The deep-sea polymetallic nodule deposits in the CCZ alone are estimated to hold an immense value of approximately 8–16 trillion USD [23]. Despite this vast financial potential, most economic assessments indicate that the viability of their extraction remains low.

As highlighted in Section 3, mining these nodules requires highly advanced equipment and infrastructure, leading to substantial capital and operational expenses. Since the necessary technologies are still immature and not widely implemented, the cost estimations remain highly uncertain, making an accurate market analysis difficult to finalize. Additionally, the financial feasibility of deep-sea mining is significantly influenced by fluctuating global commodity prices and evolving legislative frameworks.

Despite these issues, a comparative operational and financial analysis will be presented next, highlighting the differences between deep-sea and traditional land mining of manganese. In the first case, a single mining system is considered in the CCZ with high-abundance nodules of 22 kg/m<sup>2</sup>, assuming an annual capacity target of 3 million tons per annum of dry manganese nodules during the initial 20 years of exploration [76]. In contrast, a preliminary economic assessment for a low-capital, long-life manganese mining operation in North America is considered [77]. The provided financial and operational metrics are included in Table 1.

**Table 1.** Metrics of the operational and financial analysis comparing deep-sea and land-based manganese mining.

| Metrics                             | Deep-Sea Mining | Land-Based Mining |
|-------------------------------------|-----------------|-------------------|
| Yearly production (mtpa)            | 3               | 0.068             |
| Operation time (years)              | 20              | 47                |
| Capital costs—CAPEX (millions USD)  | 4000            | 350               |
| Operation costs—OPEX (USD/t)        | 16.66           | 122               |
| Annual gross revenue (millions USD) | 783.2           | 175               |
| Payback period (years)              | 5.1             | 2                 |
| CAPEX ratio                         | 5.11            | 2                 |
| Total gross revenue (million USD)   | 15,664          | 8319              |
| Total net revenue (million USD)     | 14,664.4        | 7929.09           |

The yearly production refers to the annual volume of manganese mined, indicating the scale of operations. The operation time is the duration over which the mining project is expected to operate, impacting long-term financial planning efforts. The capital costs represent the initial investment required to start the mining operations, affecting the project's financial feasibility. The operation costs are the ongoing expenses per ton of manganese mined, influencing the profitability. The annual gross revenue is the yearly income generated from selling the mined manganese, reflecting the project's revenue potential. The payback period is the time needed to recover the initial investment, which is crucial for assessing the investment risk. The CAPEX ratio is the proportion of capital expenditure to annual revenue, indicating the capital utilization efficiency. The total gross revenue is the cumulative income over the project's lifetime, showing the overall revenue generation, while the total net revenue is the cumulative profit after deducting the operational costs, highlighting the project's profitability. These metrics helped in evaluating the financial health and operational efficiency of the two considered mining projects.

The operational and financial comparison between the two mining plans reveals fundamentally different business models with distinct risk–reward profiles. The deep-sea mining project plans to operate at a large industrial scale, producing 3 million tons annually

(44 times the land-based output), enabling much lower operating costs (16.66 USD/t versus 122 USD/t for land-based). This cost advantage comes with substantial capital requirements, with a 4 billion USD CAPEX, representing an 11-fold greater initial investment compared to the land-based project, reflected also in its higher CAPEX ratio (5.11 versus 2). While the deep-sea operation may generate nearly double the total net revenue (around 14.7 billion USD versus 7.9 billion USD) over its shorter 20-year lifespan, its payback period of 5.1 years suggests longer capital recovery timelines. In contrast, the land-based mining project demonstrates superior capital efficiency, recovering its costs in just 2 years, while operating for 47 years, although at significantly lower production volumes. The most striking divergence appears in the revenue per ton; the land-based approach may achieve approximately 2600 USD/t compared to just 261 USD/t for deep-sea mining. This comparison suggests that deep-sea mining favors investors with substantial capital and risk tolerance seeking volume-driven returns, while land-based operations offer lower-risk, margin-focused opportunities with faster capital turnaround.

The costs of environmental restoration, potentially reaching 5.3–5.7 million USD/km<sup>2</sup> for the CCZ, nearly one-third of the estimated mineral value of 15 million USD/km<sup>2</sup> [78], may become mandatory for future mining operations. These significant rehabilitation expenses represent a major financial uncertainty and were not accounted for in the above financial projections.

In summary, the financial projections for manganese nodule mining in the CCZ indicate a positive return on investment only under ideal conditions. Economists warn that deep-sea mining entails significant financial and environmental risks, as previously discussed, which could severely impact the long-term profitability. These concerns have made many investors and governments increasingly cautious, viewing deep-sea mining as a high-risk venture fraught with unresolved legal, technological, and environmental challenges.

#### *4.4. Regulatory and Legal Barriers*

Regulatory and legal challenges also pose significant barriers to the advancement of deep-sea mining. Central to these challenges are unresolved issues surrounding jurisdiction, resource ownership, and the equitable distribution of benefits, as both nations and private entities vie for access to seabed mineral resources. The absence of a robust international regulatory framework exacerbates these conflicts, leaving critical questions about environmental protection, liability for ecological damage, and profit-sharing mechanisms inadequately addressed. Without clear legal guidelines and enforceable standards, large-scale commercial mining operations cannot proceed responsibly, resulting in a contentious stalemate among governments, corporations, and environmental advocates.

##### *4.4.1. Organizations and Initiatives*

In recent decades, various organizations and initiatives have been established to ensure the health of ocean ecosystems and the sustainable use of ocean resources for current and future generations. These entities play key roles in the governance, research, and sustainable management of ocean resources and the marine environment. Decision-makers have long aimed to strike a balance between protecting fragile deep-sea ecosystems and regulating mining activities in these areas.

The Intergovernmental Oceanographic Commission (IOC), established by UNESCO in 1960, was the first groundbreaking initiative for advancing international collaboration in ocean science. Its mission included promoting marine research and observation systems and sustainable ocean resource management. Today, the IOC actively supports its 150 member states in achieving global frameworks such as the UN Agenda 2030 [79], including the

Sustainable Development Goals (SDGs) [80], the Paris Agreement on Climate Change [81], and the Sendai Framework on Disaster Risk Reduction [82].

The United Nations Convention on the Law of the Sea (UNCLOS), which was adopted in 1982, provides a thorough legal framework governing marine activities. It delineates maritime zones, regulates navigational rights, and advocates for the sustainable management of resources alongside the protection of the marine environment. UNCLOS also advances marine scientific research, facilitates technology transfer, and provides mechanisms for resolving maritime disputes, fostering global cooperation and equitable benefits.

A significant outcome of this international treaty was the establishment of the International Seabed Authority (ISA), the single authority responsible for regulating mineral-related activities on the seabed, ocean floor, and subsoil beyond national jurisdiction, areas collectively referred to as the “Area”. These regions lie outside the sovereignty of any country and must be managed as the common heritage of mankind to ensure equitable benefit-sharing and environmental protection [83]. This organization exclusively grants exploration and mining licenses, ensuring the equitable distribution of benefits, particularly to developing nations. It also enforces regulations to minimize environmental harm and promote sustainable practices that safeguard marine ecosystems and humanity. Moreover, the ISA can also impose penalties or even suspend mining activities in cases of non-compliant activities [83].

A more recent significant global initiative in this field, the UN Decade of Ocean Science for Sustainable Development (2021–2030), aims to advance ocean science to support sustainable development. It focuses on enhancing the scientific knowledge of ocean systems through coordinated research, fostering cross-sector collaboration, and developing science-based solutions to tackle challenges such as pollution and climate change. The special measures include prioritizing capacity-building in developing nations and promoting ocean literacy. The initiative also supports sustainable development by providing a scientific foundation and actively contributing to the SDGs of the United Nations, particularly SDG 14 (Life Below Water) [80].

This framework also focuses on deep-sea mining, highlighting the importance of collecting essential information about vulnerable ecosystems and species before any large-scale mining begins. It stresses how crucial the ocean is to our planet and warns about the risk of losing unique marine life forever. To make well-informed decisions about this new area of exploration, the initiative calls for careful planning and independent research based on solid evidence [84,85].

#### 4.4.2. Actions Taken

In recent years, responsible organizations have taken significant steps to balance the rapidly growing demand for seabed mineral resources with the imperative need to protect deep-sea ecosystems. The most stress is obviously on the ISA.

Since the early 2000s, the ISA has been developing the so-called “Mining Code”, a set of regulations for the prospecting, exploration, and exploitation of marine minerals. It focuses on three key deep-sea resources—polymetallic nodules [86], polymetallic sulfides [87], and cobalt-rich ferromanganese crusts [88]. These regulations were developed or updated in the early 2010s. Furthermore, the ISA formulated diverse recommendations to assist potential contractors and the member states [89].

As the field rapidly changed and evolved, the earlier regulations became outdated. In 2019, the ISA began drafting revised exploitation regulations, initially aiming for completion by 2023. However, delays postponed the deadline to July 2025, despite considerable negotiation efforts among the ISA member states, endangering the control over the deep-sea mining of ISA.

In the absence of revised regulations, member states are pursuing their interests in different ways. Highly developed countries, eager to secure critical raw material resources, are pressuring the ISA to accelerate the approval process for deep-sea mining. Meanwhile, smaller nations located near exploration sites have raised concerns related to environmental protection, safety, and economic interests, advocating for stricter safeguards.

Nauru, the world's third smallest country by land area (only 21 km<sup>2</sup>), possesses significant potential for deep-sea mining. In 2021, it invoked the "two year rule" under UNCLOS, compelling the ISA to finalize regulations for proposed mining activities within two years. If the deadline is not met, the ISA must provisionally approve applications under existing guidelines [90–92]. Despite the lapse of more than two years, Nauru has not initiated mining efforts, likely due to international pressure. This pioneering action, however, accelerated discussions within the ISA, although the progress in finalizing comprehensive regulations remains slow.

Nauru's push for mining has raised alarms among the so-called conservationists, who are concerned about the potential environmental consequences of deep-sea mining, which was a central focus at the UN Ocean Conference in Lisbon in 2022. A strong coalition was established, which aimed at establishing a moratorium on deep-sea mining activities until there is a clearer understanding of the impacts on marine ecosystems [93]. The ISA was officially informed about this requirement. This was the first serious, specialist-based discussion on halting deep-sea mining [63].

Since then, more and more countries have joined this coalition, including Pacific Island nations (such as Palau, Fiji, and Samoa, which could be the most affected by the environmental consequences of deep-sea mining), member states of the European Union, and several other countries, such as Canada, the United Kingdom, and Chile. Leading environmental organizations, such as Greenpeace and the World Wildlife Fund (WWF), share the same perspective regarding these issues. Prominent scientific bodies, marine biologists, and ecologists, as well as multinational firms such as Google, BMW, and Samsung, have also publicly emphasized the need for caution and further research before advancing with such activities [94]. Their consensus is firm; seabed mining should proceed only if the marine environment is effectively protected through robust regulations. This framework must incorporate precautionary and ecosystem-based approaches, ensure transparent and science-driven management, and include stringent compliance measures supported by a rigorous inspection mechanism [95].

While deep-sea mining in the Area is largely on hold due to outdated regulations, some nations have initiated exploration activities in their national coastal waters, which fall outside the ISA's jurisdiction. The Cook Islands, heavily reliant on tourism and significantly impacted by the COVID-19 pandemic, became the first to permit deep-sea mining in their territorial waters to rebalance their economy [33]. In 2022, their government granted licenses to three companies to explore a manganese nodule deposit of approximately 6.7 Gt, the world's largest documented collection of such resources. Currently, they are studying whether mining can be performed sustainably and economically. Simultaneously, civil resistance groups are raising environmental concerns about these activities [96].

Aligned with the Cook Islands, in 2024, the Norwegian parliament approved exploration activities for deep-sea mining off the country's coast. Norway's coastal seabeds are known to contain significant deposits of polymetallic nodules and sulfides. While not among the world's top reserves, these deposits are substantial, with estimates indicating approximately 185 Mt of manganese, 45 Mt of zinc, 38 Mt of copper, 24 Mt of magnesium, and 4.1 Mt of cobalt. Norway anticipates that by 2030, it can achieve independence from imports of these critical materials through a combination of deep-sea mining and enhanced

recycling efforts, enabling the country to meet its own industrial and green transition demands sustainably.

The United States, Japan, and India seem ready to adopt a comparable strategy by commencing mineral exploration efforts in their coastal seabeds, thereby circumventing the necessity to await the ISA's regulations for the Area. This proactive approach is primarily driven by the increasing urgency related to significant shortages of critical materials, which threaten the green transition and overall sustainable development initiatives in these nations [97].

#### 4.5. Negative Social Implications

Deep-sea mining faces growing criticism for its adverse social and ethical consequences, which extend beyond the environmental risks.

##### 4.5.1. Public Opposition

The global public opposition to deep-sea mining has been growing due to the increasing awareness of its potential environmental and social consequences [98]. Environmental organizations, scientists, and Indigenous communities have raised concerns about the irreversible damage that mining could inflict on fragile deep-sea ecosystems, including habitat destruction, biodiversity loss, and the disruption of critical oceanic processes. Many activists argue that deep-sea mining should not proceed without a full understanding of its long-term ecological impact, emphasizing the need for the precautionary principle in marine resource management [99].

For example, the Metals Company (TMC), a Canadian firm and leading deep-sea mining developer, faced backlash from scientists and NGOs such as Greenpeace and Bloomberg Philanthropies over its deep-sea mining plans in the CCZ. Critics accused TMC of downplaying ecological risks, exploiting regulatory loopholes via Nauru's sponsorship, and greenwashing its operations. Legal challenges and investor skepticism stalled the project, also highlighting tensions between corporate mining ambitions and environmental protection efforts [100].

Coastal and island communities in the Pacific, the epicenter of deep-sea mining exploration, are deeply divided over whether to support or oppose seabed mining activities near their shores. While some governments and stakeholders view mining as a path to economic development (such as Nauru), others fear irreversible harm to marine ecosystems and cultural heritage [101].

The region's evolving debate underscores the global tensions between resource extraction and sustainability. Grassroots movements and new scientific evidence are driving a powerful counter-narrative centered on environmental justice, cultural preservation, and skepticism of corporate promises.

At the national level, Palau, Fiji, and Samoa are leading the opposition by confronting mining corporations, Pacific countries that are pro-deep-sea mining, and the industry-friendly ISA, challenging environmental threats to marine ecosystems, risks to vital fisheries, and what they deem neo-colonial resource exploitation, while demanding moratoriums, stricter regulations, and sustainable alternatives [99,102]. China's deep-sea mining exploration licenses in the Indian Ocean sparked protests from India and Sri Lanka, who raised sovereignty concerns over operations near their EEZs and warned of ecological threats to critical regional fisheries [103]. The dispute also highlighted growing tensions between resource exploitation and the rights of the coastal states, with both countries accusing China of disregarding the environmental risks and maritime boundaries in its pursuit of seabed minerals.

Additionally, many members of the public express concern that accelerating deep-sea mining efforts may delay or displace investments in circular economy solutions such as recycling, material substitution, and demand reduction. They argue that framing seabed mining as essential for the green transition risks creating a false sense of necessity, undermining more sustainable and less intrusive pathways. Critics further warn that this framing may amount to a form of “greenwashing”, where an environmentally harmful activity is misrepresented as environmentally beneficial. By marketing deep-sea mining as indispensable, proponents may obscure its potential for irreversible ecological damage while promoting it as a green technology. This not only risks misleading the public and policy-makers but may also erode the momentum for truly sustainable strategies aligned with long-term planetary health [104]. There is also widespread skepticism about the adequacy of global governance frameworks, the transparency of licensing processes, and the lack of inclusive participation from civil society [105,106].

These concerns are amplified by the perception that decisions are being driven by powerful state and corporate actors without sufficient consultation with or consent from those most affected. The limited scientific knowledge about deep-sea ecosystems has further intensified this public unease, as many fear that irreversible damage could occur before the full ecological consequences are even understood [107].

The public opinions on deep-sea mining remain divided and continue shifting as new studies emerge. This scientific uncertainty is keeping the issue in flux as policy-makers weigh competing priorities.

#### 4.5.2. Ethical Concerns

Beyond public protests, deeper ethical questions have emerged concerning the long-term implications and moral legitimacy of deep-sea mining. These primarily revolve around intergenerational equity and the rights of Indigenous communities [108]. Extracting mineral resources from the seabed risks depriving future generations of potential ecological and scientific discoveries, as deep-sea ecosystems remain largely unexplored. Many species inhabiting these environments have yet to be studied, and disrupting their habitats could lead to irreversible losses of biodiversity and valuable biological knowledge. Critics argue that the rush to exploit these resources prioritizes short-term economic gain over long-term planetary stewardship, contradicting principles of sustainability and responsible resource management.

Additionally, Indigenous communities, particularly in the Pacific, have strongly opposed deep-sea mining due to their profound cultural and spiritual connections to the ocean. For many Indigenous groups, the sea is not just a source of sustenance but a sacred entity intertwined with their identity and traditions. They view industrial seabed mining as a violation of their ancestral stewardship and a threat to their way of life. Resistance from these communities has fueled broader discussions on environmental justice, highlighting concerns that deep-sea mining benefits a few powerful stakeholders while disregarding the voices and rights of those who depend on healthy marine ecosystems. As the debates over deep-sea mining continue, ethical considerations remain at the forefront, emphasizing the need for inclusive decision-making that respects both present and future generations.

#### 4.5.3. Social Inequity

Deep-sea mining presents significant risks related to social inequity, as its economic benefits are likely to be concentrated among large corporations and wealthy nations, while the ecological and economic burdens fall disproportionately on small island states and coastal communities [99]. The extraction of seabed minerals requires advanced technology and substantial financial investment, which are largely controlled by developed countries

and multinational corporations. As a result, the profits and job opportunities are expected to benefit these powerful stakeholders, while the nations sponsoring such mining activities may see only minimal financial returns. Meanwhile, the communities that rely on marine ecosystems for their livelihoods face the greatest risks, with limited means to mitigate or recover from the potential damage.

Some of the most immediate threats posed by deep-sea mining are its potential impacts on fisheries and tourism, two industries that sustain millions of people, particularly in the targeted regions [109]. The destruction of seabed habitats and the creation of sediment plumes and pollution from mining activities could disrupt fish populations, leading to declining catches and losses of income for fishing communities. Similarly, the degradation of marine environments could harm the tourism industry, an essential economic pillar for many island nations. These disruptions may further exacerbate poverty and economic instability, disproportionately affecting those who are least responsible for and least capable of addressing the consequences of deep-sea mining. As the discussions around this industry continue, addressing these deep-rooted social inequities will be critical in determining whether seabed resource extraction can be pursued in a just and sustainable manner.

#### *4.6. Research Priorities and Strategic Challenges for the Future of Deep-Sea Mining*

The future of deep-sea mining hinges on overcoming significant technological, regulatory, and environmental challenges. Advancements in mining technology, including more efficient and less invasive extraction methods, will be crucial in reducing the ecological damage and improving the economic viability. At the same time, the establishment of stronger regulatory frameworks, guided by scientific research and international cooperation, is essential to ensure that deep-sea mining is conducted responsibly. Comprehensive environmental impact assessments must be prioritized to fully understand the potential consequences of disturbing deep-sea ecosystems and to develop effective mitigation strategies.

However, making informed and responsible decisions about the future of deep-sea mining requires addressing several critical research gaps. One of the foremost challenges is the limited scientific understanding of deep-sea ecosystems, where the mining activities will take place. These environments remain among the least explored on the planet, and the potential ecological impacts of seafloor disturbances, such as sediment plumes, biodiversity losses, and the destruction of fragile, habitat-forming organisms, are still poorly understood. Long-term ecological monitoring and comprehensive baseline studies are urgently needed to assess the resilience and recovery capacity of these unique ecosystems. Furthermore, the effects of deep-sea mining on carbon sequestration and oceanic biogeochemical cycles require thorough investigation, as the disruption of these processes could have wider climate implications.

In parallel, technological uncertainties remain a major barrier. While some mining prototypes have been tested, the absence of full-scale commercial operations means that the actual technical feasibility, durability, and efficiency of underwater mining systems under high pressure levels and corrosive conditions are unproven. Reliable solutions for sediment control, waste management, and environmental mitigation are still in the early stages of development and require further testing through pilot projects supported by transparent reporting.

Economic modeling under uncertainty is also a pressing research need. The current financial projections often rely on optimistic assumptions about resource prices and equipment performance, while neglecting the volatility of global markets, the hidden costs of environmental damage, and the financial risks associated with legal delays or public opposition. Realistic, integrated cost–benefit analyses that factor in environmental externalities

and long-term liabilities are essential to assess whether deep-sea mining offers a net benefit compared to alternatives such as land-based mining, recycling, and material substitution.

In addition, the governance and legal frameworks continue to lag behind the technological progress, creating a regulatory vacuum that hinders responsible investment and causes weakened environmental oversight. The ISA has yet to finalize binding regulations for mining beyond national jurisdictions, and more research is needed to develop effective legal models, inclusive stakeholder engagement strategies, and transparent policy instruments. Social science perspectives are equally important, particularly in understanding the ethical concerns, public attitudes, and potential impacts on communities, especially small, developing island states, which may be most vulnerable to the consequences of seabed mining.

Further research into deep-sea biodiversity and sediment dynamics, as well as alternative resource strategies such as urban mining, biomining, and the use of advanced recycling technologies, may offer more sustainable and socially acceptable pathways. Without clear environmental safeguards, robust governance, and financial conditions that justify the risks, deep-sea mining may continue to face strong resistance. Ultimately, the future of the industry depends on bridging these critical knowledge gaps and achieving a careful balance between global resource needs and long-term sustainability, ensuring that the economic gains do not come at the irreversible expense of marine ecosystems and the rights of future generations.

## 5. Pathways to Resolve the Paradox

Without any doubt, the technologies and legislation for deep-sea mining are not prepared for wide-scale exploration efforts. Therefore, to resolve the deep-sea mining sustainability paradox, measures must prioritize land-based solutions first. Only if terrestrial efforts prove insufficient should cautious, regulated deep-sea extraction be considered.

### 5.1. Land-First Priority

To meet the surging demand for critical materials essential for the green transition, societies must prioritize two interconnected strategies—reducing critical raw material consumption and boosting recycling rates, both reinforced by robust legislative frameworks such as the European Union’s Raw Materials Initiative and Critical Raw Materials Act.

Engineers play a central role in curbing consumption by optimizing or totally reducing the use of the most critical materials in product designs and adopting waste-free manufacturing technologies such as 3D printing [110]. Additionally, replacing scarce materials with sustainable alternatives further alleviates pressure on finite resources [6].

A significantly expanded approach to energy-efficient recycling and material substitution could complement existing efforts by substantially reducing or delaying the need for deep-sea mining. These strategies focus on recovering critical metals from existing sources while developing alternatives to resource-intensive materials.

Urban mining, which extracts metals from electronic waste, batteries, and industrial scrap, has demonstrated remarkable efficiency, often yielding higher metal concentrations than primary ores. Modern lithium ion battery recycling processes, for example, can recover over 90% of the cobalt, nickel, lithium, and manganese, dramatically decreasing the reliance on virgin materials [111]. Complementary techniques such as hydrometallurgical processing and bioleaching involve the use of chemical solvents or microbial action to extract valuable metals from waste streams and low-grade ores, presenting more sustainable alternatives to conventional mining [112,113]. Direct recycling methods offer additional promise by enabling the reuse of components such as permanent magnets and battery

materials with minimal reprocessing, preserving their functional properties while reducing energy consumption [114].

To fully realize these recycling benefits, a fundamental shift toward “design for disassembly” (DfD) principles is essential [115]. This approach requires moving away from permanent bonding techniques such as welding and the use of adhesives in favor of modular designs that allow easy component separation. Standardizing materials and parts across industries would further streamline automated sorting and recovery processes. The implementation of digital product passports (embedded data carriers containing material compositions and disassembly instructions) could significantly enhance the recycling efficiency.

Alongside enhanced maintenance and upgrade practices to prolong product lifespans, the aforementioned strategies should be bolstered by effective end-of-life collection systems to achieve high recovery rates [97].

Material substitution strategies provide another critical pathway for reducing deep-sea mining dependence. The rapid adoption of cobalt-free battery chemistries has already begun transforming the electric vehicle industry [116]. Similar progress in electrical machine design, including rare-earth-free alternatives such as synchronous reluctance and switched reluctance motors, is reducing the demand for critical minerals [4]. Even conventional materials such as copper are being substituted where possible, with aluminum increasingly being used in wiring applications to ease the pressure on copper supplies.

While these approaches may not completely eliminate the need for primary resource extraction, they collectively represent a powerful strategy for minimizing the reliance on environmentally sensitive deep-sea mining operations. By scaling up these technologies alongside supportive policy frameworks, we can create crucial breathing space to develop more sustainable long-term solutions for material sourcing.

Despite progress being made in reducing consumption rates, the use of newly mined materials remain unavoidable to meet the growing demand. Sustainable mining practices are critical to this phase, including revitalizing closed mines with greener methods and exploring new deposits under strict environmental and ethical safeguards.

By integrating all of these measures, societies can reconcile material demands with planetary boundaries, ensuring a sustainable pathway for the green transition.

## 5.2. Deep-Sea Mining

Deep-sea mining is generally regarded as a viable option only after terrestrial alternatives have been fully optimized and found to be insufficient, and even then it must be contingent on stringent environmental safeguards, including proven methods to protect marine biodiversity and restore disturbed seabed ecosystems [117].

As already stated, before any commercial operations commence, it is essential to establish environmental strategies, resolve critical technological challenges, and implement comprehensive international regulations. These measures will ensure ecological accountability, equitable benefit-sharing, and transparent monitoring. Until these conditions are met, a precautionary pause on deep-sea mining is essential to prioritize planetary health over short-term economic gains.

### 5.2.1. Environmental Protection Strategies

Ensuring sustainable deep-sea mining primarily requires a comprehensive approach that incorporates environmental protection measures at every stage of the mining process, before, during, and after operations. As the deep-sea environment is a fragile and largely unexplored ecosystem, precautionary strategies are mandatory to minimize the ecological damage and promote long-term sustainability [118].

### Pre-Mining Phase

Before any mining activity begins, a thorough environmental impact assessment (EIA) must be conducted to evaluate the potential ecological risks. These assessments should be based on extensive baseline studies that document the biodiversity, ecosystem functions, and deep-sea carbon storage mechanisms in the targeted mining areas [119].

Additionally, strategic environmental management plans should be developed, including setting up protected areas where mining is prohibited to preserve critical habitats and maintain biodiversity hotspots [120]. The adoption of the precautionary principle, which mandates that mining should only proceed if significant environmental risks are mitigated, is also crucial [121].

### Exploration Phase

During the exploration phase, environmental monitoring efforts must be integrated into resource assessment activities [122]. Low-impact exploration techniques, such as the use of remotely operated vehicles (ROVs) and AUVs, should be used to map the seabed and analyze mineral deposits with minimal disruption to the marine environment.

To ensure habitat preservation, exploration activities should follow strict biodiversity guidelines, including the collection of data on species distribution, sediment stability, and ecosystem connectivity. This information can help define no mining zones in ecologically sensitive regions, ensuring that deep-sea life is safeguarded from large-scale disturbances.

### Operational Phase

Once deep-sea mining begins, the priority is to reduce the ecological footprint of the extraction processes. Several key measures must be implemented.

Sediment plume management is crucial [123]. Technologies such as controlled suction systems and localized sediment return mechanisms should be used to minimize dispersion [49].

Additionally, selective and controlled extraction should be prioritized, with mining technologies developed to target only specific mineral-rich areas while avoiding unnecessary destruction of the surrounding environment [124]. This includes the use of precision robotic mining tools instead of large-scale dredging.

Carbon cycle preservation is also vital, as deep-sea sediments play a crucial role in long-term carbon sequestration [125]. The mining operations should ensure that the disturbance to the stored carbon is minimized, potentially through compensatory environmental programs or carbon offset strategies. Furthermore, waste and chemical management factors must be addressed, with the mining operations avoiding the introduction of harmful chemicals into deep-sea environments [126]. Closed-loop processing systems should be developed to prevent the release of toxic waste.

### Post-Mining Phase

After the mining operations are completed, habitat restoration and biodiversity recovery efforts should be undertaken.

Since polymetallic nodules, which serve as habitats for deep-sea organisms, cannot be replaced naturally within human timeframes, artificial substrate structures should be introduced to promote recolonization [127]. Additionally, setting aside previously mined regions as protected recovery zones can help facilitate the gradual return of marine species [128]. Continuous research studies on these zones using underwater drones, sensor networks, and satellite data will be mandatory to assess the long-term impacts of mining and determine the effectiveness of restoration efforts. The adaptive management strategies should be adjusted based on these findings.

By adopting these strategies, deep-sea mining can align more closely with global sustainability goals while ensuring the long-term health of marine ecosystems. However, without these measures, the risk of irreparable damage to deep-sea biodiversity and ecological processes remains high.

#### 5.2.2. Technological and Operational Developments

Developing low-impact mining technologies is critical to minimizing the ecological harm in deep-sea environments [39,129]. Precision nodule collection systems, such as advanced robotic harvesters equipped with AI-driven sensors (see Figure 9), can selectively target polymetallic nodules while avoiding fragile seabed habitats [130].

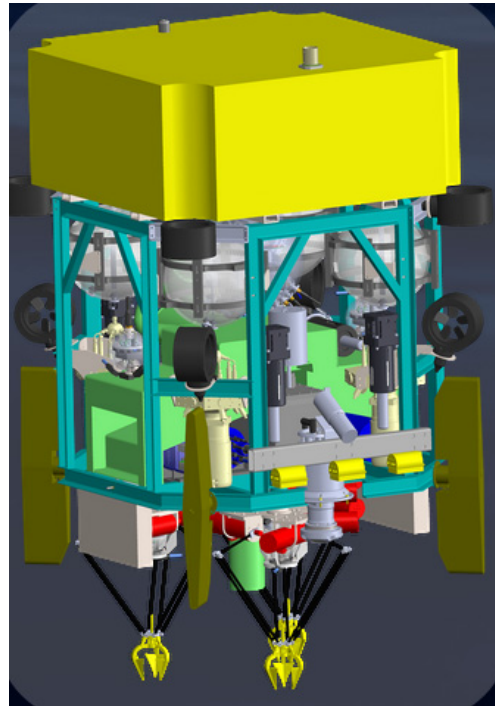


**Figure 9.** Robot driven by AI-powered computer vision system for collecting deep-sea nodules [130].

These systems leverage real-time data to adjust operations related to their movement, suction pressure, or gripper positioning, minimizing disturbances [131]. For instance, adjustable spiral-flow hydraulic suction heads lift nodules while preserving sediments [132], and precision robotic grippers allow extraction in complex terrains without collateral damage.

The use of swarm robotics, deploying small, coordinated robots, could further minimize the footprint of mining by replacing the large and disruptive underwater mining machinery [133].

As stated above, sediment plume containment remains a major challenge, as disturbed particles can smother marine life and spread toxic metals. Minimizing these impacts during deep-sea mining requires the combination of engineering solutions, environmental monitoring, and adaptive management strategies.

One of the most advanced approaches involves the use of precise sediment collection and re-injection systems. With this method, the sediment dislodged during mining is collected and re-deposited near the original excavation site rather than being allowed to disperse into the mid-water column. This strategy, often called near-bottom discharge, helps limit plume spread and retains the sediment within its native ecological zone, thereby reducing the risk of long-distance ecological disruption [134].

In parallel, the design of mining equipment plays a crucial role in minimizing plume generation. Low-disturbance vehicles, such as suction-based collectors and track-mounted systems that distribute weight evenly, reduce the extent to which the seafloor is disturbed and limit the amount of sediment resuspension [135]. Some proposed solutions also include the use of physical barriers, such as sediment curtains, which are already frequently used in marine construction and dredging operations [136]. These are designed to contain the plume within a localized area by slowing down water movement and encouraging particles to settle quickly. Although promising, these containment technologies are still largely experimental due to the complexities of operating such systems under high-pressure deep-sea conditions.

Recent trials have demonstrated that integrating real-time plume monitoring with adaptive mining equipment can radically reduce the sediment dispersion [137].

The role of AI-powered tools is critical in ensuring environmentally responsible mining. AI-driven predictive models can optimize mining paths to avoid ecologically sensitive areas, such as coral colonies or hydrothermal vent ecosystems, minimizing the disruption to marine biodiversity [138]. Additionally, AUVs equipped with high-resolution cameras and machine learning algorithms can map mining sites with centimeter-scale precision (see Figure 10). These technologies enable the identification of biodiversity hotspots, which can then be excluded from mining operations to preserve fragile ecosystems [139].



**Figure 10.** Mapping manganese nodules on the seafloor in the CCZ in a 2015 expedition with an ROV KIEL 6000 (GEOMAR—Helmholtz Centre for Ocean Research Kiel, Kiel, Germany) remotely operated vehicle [140].

Despite progress being made, scaling these technologies also requires resolving energy constraints [141] and ensuring long-term durability in corrosive, high-pressure conditions [142].

Collaboration between engineers, ecologists, and regulators is essential to align the technological advancements with planetary stewardship goals. However, at this moment, the greatest challenge facing deep-seabed mining research and development is the shortage of both monetary and human resources. This includes the limited number of individuals with the necessary expertise and insufficient funding to carry out the required work [74].

### 5.2.3. Regulatory and Governance Frameworks

All involved parties unanimously recognize that more effective regulation and governance frameworks than what currently exists are essential to ensuring that deep-sea mining is conducted in a way that minimizes environmental harm while promoting equitable economic benefits. Given the fragile and largely unexplored nature of deep-sea ecosystems,

more stringent legal and institutional frameworks must be established to oversee mining activities, enforce environmental protection, and uphold ethical resource distribution.

Unfortunately, the ISA currently lacks fully clear and comprehensive regulations specifically governing deep-sea mining, which significantly limits the advancements in this field [89]. Therefore, as quickly as possible, the ISA must take several critical steps to address the challenges and opportunities associated with deep-sea mining [143]. These actions are essential to ensure that deep-sea mining, if it proceeds, is conducted responsibly, sustainably, and in alignment with global environmental and ethical standards.

First and foremost, the ISA must finalize and adopt comprehensive regulations for the exploitation of deep-sea mineral resources. These regulations should go beyond the existing exploration frameworks and address key issues such as environmental protection standards, monitoring and enforcement mechanisms, liability for environmental damage, and benefit-sharing mechanisms for all member states, particularly developing countries. Without clear rules, commercial mining could proceed in a regulatory vacuum, risking irreversible harm to marine ecosystems [144].

In addition to establishing regulations, the ISA must prioritize the precautionary principle, ensuring that mining activities do not proceed without a thorough understanding of their environmental impacts. This includes establishing the already mentioned marine protected areas to safeguard biodiversity hotspots, requiring robust EIAs before any mining activity is approved, and setting strict limits on the scale and scope of mining operations to minimize ecological disruption [145].

Transparency and inclusivity are also critical. The ISA should ensure that its decision-making processes are transparent and inclusive by engaging a wide range of stakeholders, including scientists, environmental organizations, industry representatives, and member states. Draft regulations, meeting minutes, and scientific data should be made publicly accessible, and developing countries must have a meaningful voice in decision-making, particularly in benefit-sharing discussions. Transparency builds trust and ensures that the interests of all stakeholders, including future generations, are considered.

Scientific research is another priority. The ISA must invest in funding and collaboration to fill critical knowledge gaps about deep-sea ecosystems and the potential impacts of mining. This includes supporting independent research on deep-sea biodiversity, ecosystem functions, and the long-term effects of mining, as well as developing baseline data to assess environmental changes caused by mining activities. Informed decision-making requires a solid scientific foundation, which is currently lacking in many deep-sea environments [146].

#### 5.2.4. Scientific Precaution and Informed Decision-Making

Implementing a precautionary approach to deep-sea mining is crucial to preventing irreversible ecological damage. Given the vast knowledge gaps regarding deep-sea ecosystems, advocating for moratoriums until comprehensive baseline studies are conducted is essential. These studies should assess biodiversity, ecosystem functions, and potential long-term disturbances caused by mining activities.

Additionally, prioritizing independent research on the ecological impacts of deep-sea mining will provide unbiased data to inform decision-making and regulatory frameworks. Without a thorough understanding of these environments, proceeding with large-scale extraction poses significant risks to marine biodiversity and the broader oceanic system.

## 6. Conclusions

The growing demand for critical materials essential to the green transition and sustainable development has intensified concerns over supply shortages, prompting the exploration of deep-sea mining as a potential solution. Undersea mineral deposits hold

vast reserves of key elements required for clean energy technologies, electric vehicles, and advanced industrial applications. However, while deep-sea mining presents an opportunity to diversify material sources and reduce the reliance on geopolitically unstable supply chains, it also introduces significant environmental, technical, economic, and social challenges that must be carefully addressed.

Technological advancements related to nodule collection, vertical transport, and surface processing have made deep-sea mining increasingly viable, yet major uncertainties remain regarding its environmental footprint and financial feasibility. There is the risk of irreversible damage to the fragile and largely unexplored deep-sea ecosystems from mining activities, and the current regulatory frameworks, led by the ISA, lack clarity and comprehensive enforcement mechanisms. Moreover, the economic viability remains uncertain due to the high operational costs, fluctuating commodity prices, and competition with land-based mining and recycling initiatives.

To navigate this sustainability paradox, a balanced approach is required, one that prioritizes responsible resource extraction while safeguarding marine ecosystems. The pathways to solutions include the development of stricter regulatory and governance structures, advancements in environmentally conscious mining technologies, and a commitment to precautionary scientific research. Land-based solutions such as improved recycling and substitution efforts and more efficient material use should be prioritized wherever possible, while deep-sea mining, if pursued, must adhere to rigorous environmental protection standards, sustainable operational models, and equitable economic benefit-sharing.

Ultimately, deep-sea mining must be approached with caution, ensuring that technological progress does not come at the expense of ocean conservation. Only through a holistic, science-driven, and ethically sound strategy can deep-sea mining contribute to a truly sustainable future, balancing the urgent need for critical materials with the long-term health of our planet's marine environments.

It is important to note that all conclusions presented in this paper are based solely on a synthesis of the published literature and do not represent personal viewpoints or advocacy positions.

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