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Development of Deep-Sea Biological Resources Exploitation Equipment

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Abstract: Extreme deep-sea environment has resulted in the development of the largest ecosystem in the world, which is far from discovered completely. The deep-sea environment possesses several biological resources with special functions. Exploitation equipment is important for promoting green, safe, and orderly development of deep-sea biological resources. To clarify the characteristics and technical challenges of the equipment for deep-sea biological resource exploitation and explore its development directions and focus, we investigate the technical requirements of deep-sea biological resource exploitation, present the current status of deep-sea biological resource exploitation equipment, and analyze the challenges faced in the development of this equipment. To overcome difficulties, such as lack of unified standards, shortage of testing platforms, and deficiency in technology transformation, we propose several suggestions from the perspective of innovation systems, general technology, transformation platforms, and international cooperation, with the objective of contributing to the sustainable development of deep-sea biological resources from the equipment development perspective.

Keywords: deep sea; biological resources; *in situ* observation; sample; *in situ* experiment

1 Introduction

The extreme deep-sea environment, which includes high pressure, darkness, extremely high/low temperatures, and oligotrophic conditions, favors the development of special geological systems, such as hydrothermal vents, cold seeps, seamounts, whale falls, and abyssal plains, which are rich in macrobiotic, microbial, and genetic resources [1]. The exploration and exploitation of these special systems rich in biological resources facilitate the understanding of the origins and evolution of extreme life forms and deciphering the multi-layer interactions at the Earth's depth. Biological resources adapted to the extreme deep-sea environment could be a source of compounds with novel structures that are different from those on land and offshore. Such compounds may have unique functions and might be useful in medicine, food, novel energy materials, microbial fertilizers, and petroleum sewage degradation, among other applications. Therefore, the development of these special biological resources is crucial for the development of agriculture, medicine, modern materials, and environmental protection. Deep-sea biological resources represent an important national strategic reserve resource that requires urgent development.

The deep-sea biological resource exploitation equipment is a general term for any equipment that is used for the exploration, observation, acquisition, preservation, and cultivation of deep-sea biological resources. Such equipment adapts to extremely harsh conditions in the deep sea by exhibiting the characteristics of pressure resistance, temperature resistance, and corrosion resistance. The research and development associated with

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advanced deep-sea biological resource exploitation equipment have a special role in promoting green, safe, and orderly development of deep-sea biological resources, which successively supports the development of deep-sea access, deep-sea exploration, and deep-sea development. Compared to life on land and offshore, knowledge regarding deep-sea biological resources is limited. To enhance China’s deep-sea biological resource exploitation capabilities, the present work analyzed the demand for deep-sea biological resource exploitation equipment, examined the development and characteristics of related equipment in China and abroad, and proposed countermeasures and suggestions for resolving the development problems associated with China’s equipment.

2 Demand for deep-sea biological resource exploitation equipment

2.1 Current demands

Life in the ocean is believed to have existed for three billion years. Life on Earth is supposed to have originated in the deep sea, followed by migration to land and evolution thereafter. Therefore, the study of life in the deep sea is useful for deepening the understanding of the origin of life. Owing to the limitations in equipment technology, the understanding of deep-sea life forms is limited. The deep sea was once regarded as the “forbidden zone of life” and it has required over 150 years of deep-sea exploration to understand the diversity and specificity of deep-sea life systems. With advances in deep-sea biological resource exploitation equipment technology, the understanding of deep-sea biological resources has deepened, and knowledge on deep-sea ecosystem service functions has strengthened. However, humans know only approximately 20% of the deep seabed, and most of these observations and explorations are limited to local studies [2]. Therefore, it is imperative to develop advanced deep-sea biological resource exploitation equipment to provide technical means for exploring and using deep-sea biological resources. It is necessary to study the development and characteristics of such equipment and to determine the objectives and development direction of such equipment technology.

2.2 Demand for technology

Oceans cover 71% of the Earth’s surface, more than half of which is deep-water (3000–6000 m) (Fig. 1). The vast deep-sea regions form the largest ecosystem on Earth, comprising the largest number of living organisms, the largest biological populations, and the richest biological gene resources [3]. To retrieve these special biological resources from the deep sea, it is necessary to develop special equipment suitable for deep-sea environments. On one hand, such equipment must possess strong pressure-retaining characteristics because the deep-sea environment is characterized by high hydrostatic pressure, low temperature, hypoxia, and high salt, with some regions containing certain unique corrosive chemicals; the gene expression characteristics of deep-sea organisms may change after they leave a special deep-sea environment, some of which are rare biological resources, such as cold-water corals and deep-sea tube worms, are easily broken in the process of moving and retrieval. On the other hand, the equipment must possess high-pressure resistance and exhibit efficient anti-corrosion performance. For instance, because deep-sea biological resources are widely distributed, the exploration and sampling process involves strict requirements for depth, operating range, and undisturbed sampling of the equipment. Therefore, elucidating the technical characteristics and development path of deep-sea biological resource exploitation equipment and breaking through the core technologies of deep-sea equipment are important approaches to protect the diversity of deep-sea biological resources and ensure their sustainable development.

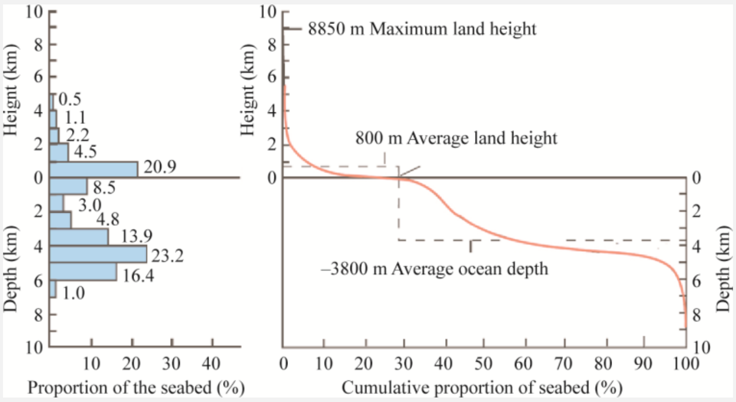

Fig. 1. High-resolution bathymetry map of the world [2].

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3 Development of the deep-sea biological resource exploitation equipment worldwide

3.1 Exploitation and observation equipment

In situ exploitation and observation are important means for studying the species, distribution, and characteristics of deep-sea biological resources. An important observation and exploitation method is the identification of deep-sea organisms using optical and acoustic technologies. With advances in optical imaging technology, deep-sea organisms can be observed and imaged at the micron, centimeter, and meter scales. Deep-sea diving equipment and deep-sea landing devices equipped with optical imaging technology can identify and observe deep-sea biological species and ecosystem resources within the range of hundreds of kilometers, in vertical sections and along horizontal scales.

Emerging technologies, such as holography, structured lighting, *in situ* plankton imaging, and 3D imaging, provide new opportunities to identify key biological species and ecosystem understanding in the deep sea. In 2005, the Russian Academy of Sciences developed an animal sample counting system to study the vertical distribution of macroplankton in the Charlie-Gibbs Fracture Zone with the manned submersible “Mir-1” and “Mir-2”, meanwhile, the zooplankton abundance was quantitatively estimated at different depths [4]. In 2008, the French LOV laboratory employed an underwater video profiler to estimate the vertical distribution (0–1000 m) of macrozooplankton in the northern portion of the Mid-Atlantic Ridge. The instrument could automatically identify macroorganisms and was particularly suitable for the quantitative study of fragile and gelatinous plankton [5]. In 2009, to observe the benthic boundary layer communities for a long duration, the Monterey Bay Aquarium Research Institute employed an acoustic split beam array and a subordinate digital delay camera system, achieving a breakthrough in the application of long-term autonomous operation in a wired underwater network along with real-time data transmission to the land base. In 2012, scholars from New Zealand connected a remote underwater video system with a 1500 m-long submarine pipe network, which enabled real-time monitoring of changes in the structure and diversity of fish communities at different depth gradients along with a feedback image data transmission [6].

High-throughput technologies, such as deoxyribonucleic acid (DNA) sequencing and mass spectrometry, have facilitated the observation and exploration of deep-sea biological resources by enabling the direct monitoring and analysis of the environmental DNA (eDNA) characteristics of the biological populations, which enables the clarification of the diversity of deep-sea biological populations without sampling. Currently, the effectiveness of the genome-related methods used to investigate deep-sea prokaryotes, microorganisms, and metazoan communities relies on deep-sea species identification methods, such as metagenomics, metatranscriptomics, metaproteomics, and metabolomics. Only by coupling omics data with other deep-sea observation data and biological culture data, it is possible to reconstruct the deep-sea ecosystem and fully understand the characteristics of deep-sea biological resources [7].

The observation and exploitation of deep-sea biological resources have greatly improved with the development of various deep-sea diving equipment technologies, such as human-occupied vehicles (HOVs), remotely operated vehicles (ROVs), and autonomous underwater vehicles (AUVs). In 1977, a deep-sea hydrothermal ecosystem was discovered using diving equipment, followed by determining the distribution in deep-sea ecosystems, such as hydrothermal ecosystems and cold seeps, and discovering novel species through diving observations [8]. Currently, ROV and AUV are widely used due to their wide operating range and strong flexibility. Over time, the global marine power has formed a complete equipment pedigree, covering 3000-m deep seas, 6000-m hadal, and 11 000-m full-sea depth operations, using diving equipment, underwater communication facilities, and surface-support mother ships. This generated key capabilities for the *in situ* observation and exploration of the biological resources in trenches and deep seas. The United States, Canada, China, Japan, Australia, France, and Germany are the main countries developing related equipment, while the United States, China, and Japan have demonstrated outstanding capabilities in deep-sea equipment.

3.2 Acquisition and preservation equipment

Effective acquisition and preservation of deep-sea organisms is a prerequisite for the exploitation of deep-sea biological resources. Several countries worldwide have progressed rapidly in deep-sea biological sampling (Table 1) [9]. The New Zealand National Institute of Water & Atmosphere has developed a relatively lightweight trawling net with a bridle-and-chain separation system to sample macro-invertebrate assemblages on seabed topography and substrates [10]. The *in situ* trapping chain hook equipped with a camera system proved to be an effective device for capturing macroorganisms and microfauna in soft substrates. The Royal Netherlands Institute for Sea Research developed a deep-sea dredger composed of a metal frame, trawling net, and blade, which could efficiently collect epibenthos samples [11]. The sample-selector is used to collect small deep-sea organisms and is suitable only for biological acquisition from soft substrate sediments.

Table 1. Types of deep-sea biological resource exploitation equipment.

Equipment type	Biological type	Sediment type
Purse seine/Fishing net	Fish, macro-invertebrates (especially sessile and zooplankton)	Soft flat sedimentary environment in all habitats
Diving equipment	Macro-invertebrates and microorganisms	All habitats and sediment types
Bottom surface trawling net	Macro-invertebrates and epifaunas	According to trawling net type
Chain hook	Large and small attached animals	Only suitable for soft substrate
Sample-selector	Small animals	Only suitable for soft substrate

The mechanical arm of the diving equipment is equipped with a sampling device that can collect deep-sea organisms from various habitats and geological forms (Fig. 2). In 2005, the Monterey Bay Aquarium Research Institute developed a debris sampler to collect extremely vulnerable mid-layer aquatic animals, such as jellyfish and larvae, on the *in situ* ROV. With the increasing demand for deep-sea biological samples, robotic systems with maneuverability similar to that of humans have become the focus of deep-sea research. In 2018, the University of Rhode Island developed a soft robotic arm that could sample at a water depth of 2300 m by controlling a glove-based gripper, and the material used was suitable for soft and fragile marine organisms [12]. In 2018, to achieve accurate sampling while effectively protecting the samples, Harvard University developed soft robotic manipulators from flexible materials using the additive manufacturing process, which improved the stability of the soft manipulator during operation. The manipulators added interactive “nails” in the soft fingertips for a flexible grasping of the samples present on hard substrates [13].

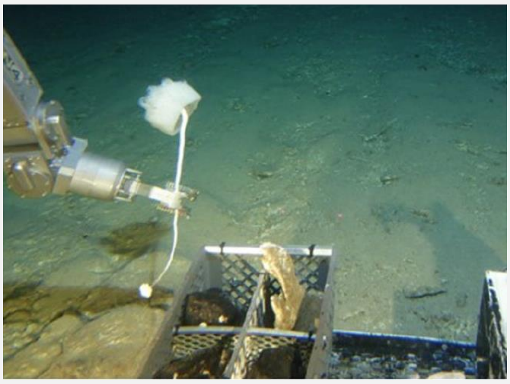

Fig. 2. The ROV robotic arm captures deep-sea sponge.

Research on deep-sea biological resource sampling equipment focuses on accurate sampling under extreme deep-sea environments without disturbing deep-sea organisms, keeping the *in situ* environment of deep-sea organisms unaltered, and expanding the functional diversity of the equipment. In 2019, the French LOV laboratory integrated *in situ* sampling, enrichment, and transfer of deep-sea organisms within a single equipment [14].

4 Current developments in the deep-sea biological resource exploitation equipment in China

In line with the global development of deep-sea biological resource exploitation equipment, China’s marine strategy and deep-sea biological exploitation research and technology have made great progress. Since 2014, particularly during the 13th Five-Year Plan period, China’s deep-sea biological resource exploitation equipment technology and other related technologies have progressed rapidly. These technologies have now been incorporated into the national biological resource exploitation strategic plan, including biological pressure-retaining sampling, fidelity storage, and biological cultivation (Fig. 3). Currently, active-capture, fixed-trapping, and *in situ* sampling and enrichment of microorganisms are the key technologies for deep-sea biological exploitation in China, in addition to the pressure-retaining transfer and fidelity storage equipment, which represent the key research directions (Fig. 4).

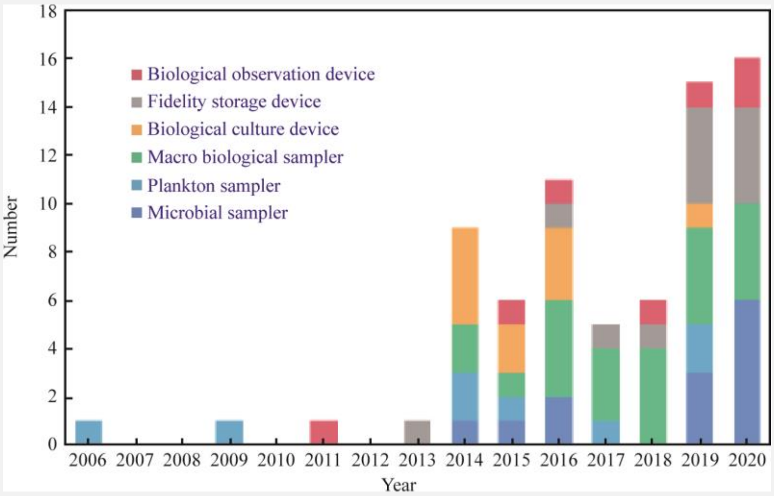

Fig. 3. Patent development of China’s deep-sea biological exploitation equipment.

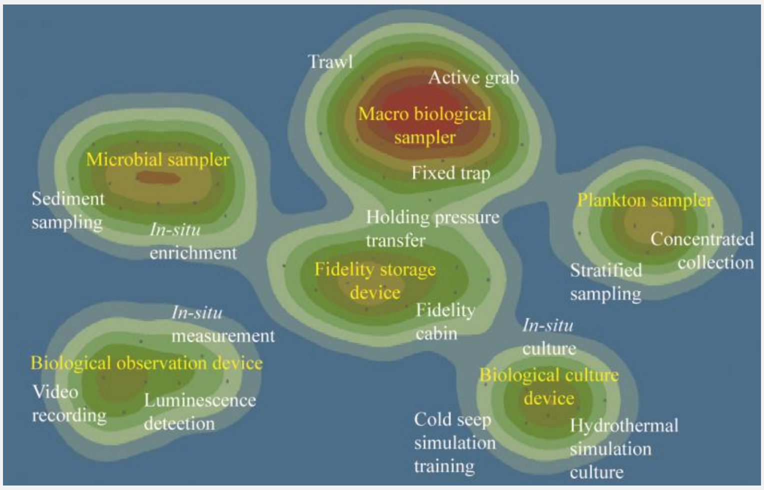

Fig. 4. Patent hotspots of China’s deep-sea biological exploitation equipment.

4.1 Deep-sea microbial sampling and enrichment equipment

Deep-sea biological sampling and enrichment equipment capacity determines the efficiency of resource use. Related research is focused on developing equipment that has a simple structure and flexible operation and allows *in situ* pollution-free pressure-retaining sampling, continuous long-distance sampling, pollution-free sampling, and pressure-free mutation sampling, along with high-abundance enrichment and long-term preservation. Currently, the key technologies in China are multi-point sampling, pollution-free and pressure-free mutation sampling, high-pressure sampling cylinders, and large-flow filtration with multi-pleated membranes.

The research team of Zhejiang University developed a series of deep-sea microbial sampling and enrichment devices that can work independently on the seabed or are equipped with ROVs for mobile work, with sampling depths ranging from hundreds to 6000 m. These devices perform deep-sea environment microbial sampling and enrichment via pumping, grasping, different cyclic filtration levels, and protection of the vulnerable RNA samples with fixing solutions. The microbial sampling device developed by the research team of Central South University can achieve a maximum concentration ratio of 500 and a sample pressure change of less than 5% obtained within 6 h [15].

4.2 Sampling, observation, and trapping equipment for deep-sea macroorganisms

Deep-sea macroorganisms live under extreme environmental conditions of high pressure and extremely low or high temperatures, and the expression of the genetic material of the biological samples may change significantly upon separation from the *in situ* environment during the exploitation process. The technological requirements are pressure- and temperature-retained, rapid, and accurate sampling equipment, and the trapping equipment with agility, flexibility, pertinence, and high trapping rate. Macrobiological sampling equipment developed in China, including the digging, shoveling, and trawling types, is used mainly for the *in situ* sampling of deep-sea macroorganisms, and can also be integrated with trapping devices.

The focus of the sampling equipment is to retain the extreme pressure and temperature environment in which the biological samples originally resided. To overcome the problem of traditional biological trawl nets causing damage to fragile benthic organisms, deep-sea biological larva pressure-retained samplers for multiple subsection/layered nets [16] and deep-sea biological larva samplers [17] were developed in China, which enabled remote video monitoring and sampling operations. The developed deep-sea macrobiological trapping device, mainly composed of luring traction parts and closed parts, may be used with the ROV operating platform or fixed independently on the seabed *in situ*. For instance, the trapping equipment developed by Shanghai Ocean University achieved real-time and complete sampling of deep-sea macroorganisms.

In the field of macrobiological observation, an underwater video and data transmission system based on optical cable, a deep-sea video system based on optical composite cable [18], and a high-definition deep-sea camera system based on biometrics and classification have been developed in China, and biometric identification in the sampling process has been achieved with an accuracy rate of 80% for intelligent classification of samples.

4.3 Deep-sea biological cultivation equipment

Deep-sea organisms are exposed to special living conditions, due to which some organisms are thermophilic and psychrophilic, while others are halophilic and hypertrophic. An effective approach to exploit and use deep-sea biological resources is deep-sea *in situ* colonization, which involves “transplanting” the marine microbial culture media and the culture methods commonly used in laboratories on land into the deep-sea seabed, enriching and cultivating deep-sea organisms under deep-sea *in situ* high pressure, low temperature, oligotrophic, and no light conditions. Currently, existing devices are used mainly for the *in situ* enrichment and culture of microorganisms. These devices can work autonomously in a deep-seabed environment and can measure the changes occurring in the environmental parameters. The development direction of the related equipment includes developing equipment for long-term *in situ* microbial colonization, autonomous sensing and recording of the environmental parameters, directional induction enrichment and intelligent control, and developing intelligent culture equipment for deep-sea macroorganisms under *in situ* directional condition control.

The deep-sea water *in situ* colonization culture systems developed in China can remain in the deep-sea environment for a long time. In addition, 16S rRNA gene high-throughput technology and isolation and culture methods were applied to develop a research facility for microbial aggregation diversity. The developed *in situ* culture system for deep-sea sediments can be placed and recycled at a fixed point for visualization at a depth of 6000 m, can be recovered visually, and can also be placed on deep-sea sediments to add nutrients to adjust the local culture environment for *in situ* colonization [20]. The research team of Zhejiang University developed an autonomous *in situ* observation device for a deep-sea experimental ecosystem that could conduct artificial induction culture in a deep-sea *in situ* environment and recorded the development process of the ecosystem [21].

Regarding land-based simulation cultures, several deep-sea microbial culture systems with a maximum simulated pressure of 60 MPa have been developed by the third Oceanographic Research Institute of the Ministry of Natural Resources, Shanghai Jiao Tong University, the Zhejiang University, the Ocean University of China, the Institute of Deep-sea Science and Engineering, the Chinese Academy of Sciences, and the Harbin Institute of Technology. These developed systems have conducted deep-sea high-pressure and anaerobic environment simulation tests in land laboratories or scientific research ships and have also established a continuous culture of microorganisms in hydrothermal and cold seep regions [22]. Shanghai Jiao Tong University simulated the eruption environment of deep-sea cold seeps in the laboratory using deep-sea environment simulation technology and proposed a new model for the cold spring carbon cycle [23].

It is noteworthy that land environment simulation equipment developed in China presents certain limitations in design and manufacturing when they are used to develop deep-sea biological resources. For instance, continuous and high-precision pressure and temperature control capabilities must be strengthened. In addition, further studies on accurate online monitoring capabilities for the key indicators of deep-sea living environments, including dissolved oxygen, hydrogen sulfide, and carbon dioxide, are required.

4.4 Deep-sea biological resource exploitation diving equipment

China’s deep-sea diving equipment pedigree has seen rapid development in recent years, with the diving depth being constantly updated (Fig. 5), providing indispensable equipment and the required technical support for the development of deep-sea biological resources.

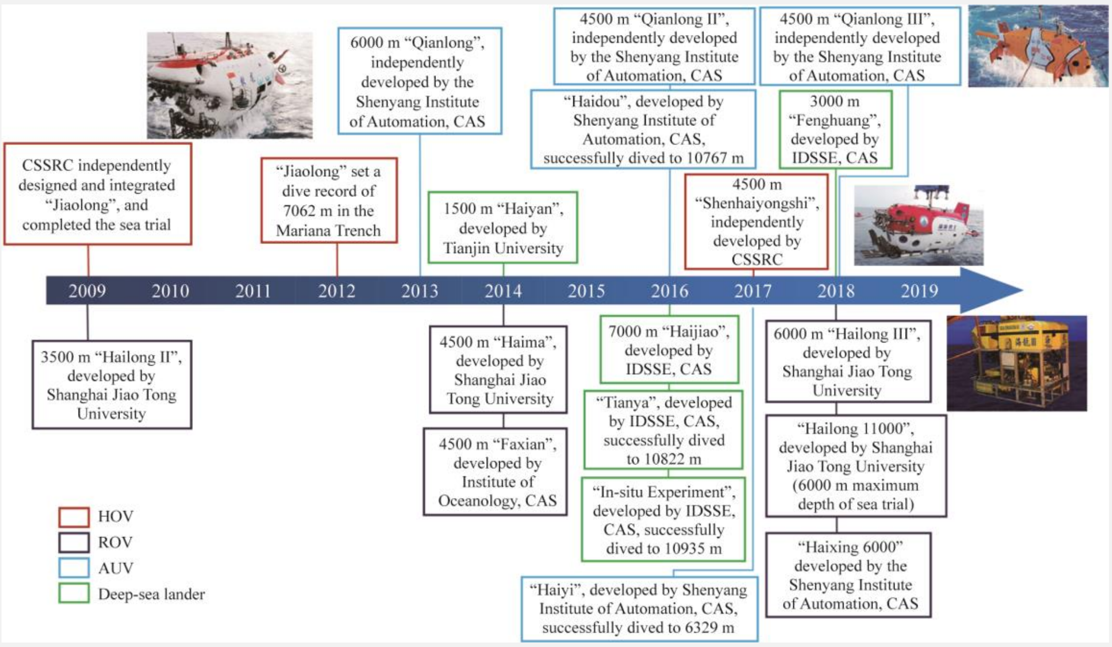

Fig. 5. Development of deep-sea submersible equipment in China.

Regarding manned deep-sea submersibles, the “Jiaolong” and “Shenhaiyongshi” conducted a pressure-retaining sampling of organisms in a cold seep region, and the samples were brought to the laboratory for analysis and culture [24,25]. Scientists who developed manned submersibles discovered rich and diverse hydrothermal macrobiological communities, collected large amounts of hydrothermal fluid and hydrothermal macrobiological samples, and generated important basic data and samples, which were analyzed for further investigation of material circulation, life evolution, adaptation mechanism, and impact on the ecological environment of the modern submarine hydrothermal fluid system.

Furthermore, several types of unmanned submersibles for scientific research, operation, and observation, have been developed in China. The development of unmanned submersible equipment has been completed, and includes the ROV represented by “Hailong,” “Haima,” and “Faxian,” and the AUV represented by “Qianlong,” “Haidou,” and “Haiyi.” These unmanned submersibles can support deep-sea observation, shooting, and video recording, conduct large-span, long-distance, and near-bottom observations and sampling, along with a refined operation capability. These submersibles captured a large number of deep-sea biological sample images during diving, along with several cold-seep biological samples, such as *bathymodiolus platifrons*, squat lobsters, tube worms, ophiurothamnus, and saccellas. Over 200 marine biological samples were collected, including crinoids, sea anemones, sponges, shrimps, frogfishes, aplysias, ascidians, and placopecten magellanicus. Therefore, the samples produce rich basic data for the study of deep-sea biological evolution history and ecosystem structure [26].

To meet the research requirements for abyssal organisms, deep-sea landers are usually equipped with conductive-temperature-depth sensors, dissolved oxygen sensors, high-definition cameras, water bottles, biological traps, sediment samplers, and microbial *in situ* enrichment samplers, among other devices [27]. China has developed the 1500-m “Haiyan,” 7000-m “Haijiao,” 10 000-m “Tianya,” and an “*in situ* Experiment” deep-sea lander, which have all successfully conducted the *in situ* microbial culture experiments on nitrogen cycling and ammonia oxidation at the bottom of the abyss on the seabed at 10 000 m. Over 2000 large biological samples obtained using this equipment from various depths produce valuable scientific research data for exploring the origins and evolution of the abyssal species, genetic characteristics of the populations, and the adaptation mechanisms of symbiotic microorganisms existing in extremely high-pressure environments [28].

5 Problems encountered by deep-sea biological resource exploitation equipment developed in China

5.1 Lack of superior design and unified technical standards

To date, China does not have a national-level development plan for deep-sea biological resources, resulting in an unclear top-level design. Although relevant departments have independently formulated certain industry-level development plans, there are still problems with overlapping boundaries and inferior redundant construction. Certain equipment and technologies exhibit industry-level standards; however, there is a lack of unified national standards, which is not conducive to an efficient transformation of equipment technology. Moreover, the manufacturing level of the related prototype technology is unbalanced, and the measurement data interface is not compatible, affecting the efficient acquisition and processing of deep-sea environmental data.

5.2 Insufficient research and development of general deep-sea equipment

Despite the independent research and development of certain deep-sea biological instruments and equipment in China, there are certain limitations, such as fewer equipment types, weak technological innovation, inferior intelligence levels, and low long-term stability. Moreover, most deep-sea equipment or technologies continue to be in the digestion and absorption stages long after their introduction. China is far behind the marine powers in terms of general supporting technical equipment, such as deep-sea special materials, power, communication, navigation, and operation equipment. The medium- and high-end products and key components produced by China account for less than 40% of the market share, with large-scale and high-precision *in situ* culture and sampling equipment mostly imported [29].

5.3 Insufficient equipment testing field construction

Problems encountered in the deep-sea environment, such as extreme pressure, seawater corrosion, attachment of biological materials, and communication difficulties, render scientific research in this area risky and expensive. China has progressed significantly in deep-sea technology; however, the level of application, maintenance, and management of deep-sea biological resource exploitation equipment is not sufficiently high. This results in high investment costs without sufficient returns and impact on the follow-up scientific investigation. China is far behind the maritime powers in terms of the deep-sea biological research level and talent capability. For instance, the average annual diving times of submarines in China are significantly lower than those of maritime powers such as the United States and Japan. In addition, China lacks national-level, open, dual-use, multi-functional experiment platforms and marine testing fields, as well as the capability to provide testing services and support for the evaluation of deep-sea exploration equipment.

5.4 Insufficient transformation rate of scientific and technological achievements

China has numerous marine scientific research institutions and personnel with strong marine scientific research capabilities, reflecting its relative advantages in deep-sea technology and equipment development. However, much of China’s marine scientific and technological achievements are in the “laboratory” stage, and there is no clear mechanism for the transformation of these achievements in the exploitation of deep-sea biological resources. Moreover, the progress of practical applications is slow, resulting in a lower degree of transformation of scientific and technological achievements into actual productivity [30].

5.5 Hard to industrialize deep-sea technology and equipment

China’s deep-sea equipment technology is in the stage of equipment integration and innovation, and the main components are imported . Generally, the research and development of deep-sea technology and equipment has a long lifecycle, high cost, and low demand. The high investment risk results in a low level of enthusiasm for social resources to participate in construction. The majority of deep-sea technology research and development personnel are based in universities and research institutes, and the related research and development funds rely highly on government investment. Since there is no proper integration of deep-sea technology research and development with the market mechanisms in China, it lags behind the marine powers in terms of the degree of industrialization of deep-sea technology and equipment.

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6 Countermeasures and suggestions

6.1 Developing a scientific and technological innovation system for manufacturing deep-sea biological resource exploitation equipment

The present report proposes to increase the formulation pace of national plans, technical standards, and specifications for the development of deep-sea biological resource exploitation equipment to promote their standardization. The combination of industry, universities, and research institutes should be emphasized, enterprises should be encouraged to participate in the transformation of scientific research achievements, and industrialization of deep-sea technology and equipment should be promoted. In addition, long-term and stable incentive policies should be formulated to support the manufacturing industry for deep-sea biological resource exploitation equipment.

6.2 Development of general supporting technologies for deep-sea biological resource exploitation

It is recommended to conduct general technology research on deep-sea technology and equipment represented by deep-sea special materials to ensure that the overall level of deep-sea biological resource exploitation in China meets the independent industrial development requirements. In addition, the systematic capability of developing the key basic parts of deep-sea biological resource exploitation equipment should be developed to ensure the self-reliant development and production of key equipment in the nation. Furthermore, establishing several enterprises with independent intellectual property rights and market competitiveness should be supported to promote the serialization, industrialization, and marketization of the general technologies and equipment related to deep-sea biological resource exploitation.

6.3 Establishing a national-level platform for testing and achievement transformation of national deep-sea biological resource exploitation equipment

There should be active implementation of the *National Marine Development Plan Outline*, the *National Deep-Sea High-Tech Development Special Plan (2009–2020)*, and the *Marine Science and Technology Innovation Special Plan of the 13th Five-Year Plan*. Moreover, a national marine science and technology sharing service platform, laboratory, and testing site should be constructed. Additionally, construction of national-level public testing platforms and deep-sea testing fields for the developed deep-sea exploration equipment, which are operated according to an enterprise-oriented and business-oriented model is recommended. A major layout of the country's marine field should be developed, along with the construction of several national engineering centers and enterprise technology centers for the implementation of industry–university–research integration and the acceleration of the industrialization of deep-sea exploration equipment manufacturing.

6.4 Deepening the international cooperation in the field of deep-sea biological resource exploitation equipment

The deep-sea biological resource exploitation is still an emerging field. Therefore, the active promotion of exchanges and strategic cooperation with international organizations and foreign marine scientific research institutions would be beneficial while striving to seize opportunities in the field of deep-sea biological resource exploitation. In the context of changed scenarios of international cooperation in the post-pandemic situation, it is important to effectively strengthen blue economic cooperation with countries along the Belt and Road and establish a multilateral participation model with the marine powers in research related to biological resource exploitation equipment. A joint research plan in the general key technologies field should be formulated with other nations to promote a rapid, healthy, and sustainable development of the deep-sea biological resource exploitation equipment manufacturing industry.

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