Application of Marine Bacteria in Environmental Remediation

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Abstract. The marine ecosystem plays a pivotal role in the geochemical cycle. However, since the Industrial Revolution, the problem of marine pollution has become increasingly severe. Pollutants such as heavy metals, plastic waste, and petroleum hydrocarbons have accumulated in large quantities in the ocean. Marine microbacteria possess great potential in the field of environmental remediation due to their unique living environment and the existence of numerous populations that have yet to be discovered by humans. This paper provides a detailed examination of the applications of marine bacteria in the remediation of heavy metal, plastic, and petroleum hydrocarbon pollution. It lists numerous existing research cases and introduces some research achievements related to the identification and isolation of target bacteria. At the same time, it highlights some technical obstacles in current research. For example, marine bacteria are difficult to culture, which makes it impossible to explore their action mechanisms thoroughly. Additionally, when using microbial agents for environmental remediation, it is challenging to determine the most effective methods for minimizing adverse impacts while achieving the desired remediation effect. Therefore, in the process of transforming marine bacteria into a powerful means of bioremediation, it is still necessary to seek breakthroughs by leveraging cutting-edge biological technologies.

Keywords: Marine Bacteria; Bioremediation; Heavy Metal Pollution; Plastic Pollution; Petroleum Hydrocarbon Pollution.

1. Introduction

The marine ecosystem, the largest ecosystem on Earth, covers approximately 71% of the Earth's surface and plays a crucial role in the geochemical cycle. Since the Industrial Revolution, the intensification of human activities has led to pollution of the marine environment. A large amount of polluted waste, including heavy metals and plastic debris, accumulates in the ocean, endangering the lives of various organisms and posing a threat to human health through the food chain. Nowadays, the academic community is more inclined to explore more environmentally friendly bioremediation methods to reduce costs and avoid secondary pollution.

Marine microorganisms are a vital component of the marine ecosystem, providing the initial energy source for the marine food web and playing a crucial role in promoting material cycles within the ocean. Marine microorganisms play a vital role in the cycling of common elements through various processes, including photosynthesis, heterotrophic decomposition, nitrogen fixation, nitrification, denitrification, phosphate absorption, sulfide oxidation, and other mechanisms. Furthermore, marine microorganisms participate in the cycling processes of various other elements. For instance, a study has shown that *γ-Proteobacteria* play a significant role in the arsenic cycle, which also provides scientists with the idea of exploring marine microorganisms to find approaches for reducing pollution caused by specific substances [1].

Nowadays, the cultivation of microorganisms has become a challenging problem in the path of human utilization of microorganisms, with more than 99% of microorganisms considered unculturable by humans. In addition to searching for new microbial cultivation methods, screening target strains from corresponding environments is also an essential means of identifying culturable microorganisms. Bacteria in the marine ecosystem, due to their adaptability to high-pressure and cross-salt environments, have a greater potential to contain strains with strong tolerance and high degradation efficiency towards marine pollutants [2]. Through the cultivation of specific strains, after comprehensive research on them, various microbial agents can be produced and widely applied to fields such as agriculture and pollution control at a lower cost. There are significant differences between marine microbial populations and terrestrial microbial populations, from which strains with relatively rare functions are expected to be obtained to fill the gaps in the functions of previous microbial products. Therefore, marine microorganisms have great potential in environmental governance. In recent years, technological breakthroughs in genomics, metabolomics, and synthetic biology have shed light on the molecular mechanisms of marine bacteria in pollutant degradation networks and cross-species collaborative metabolism, offering new insights into harnessing marine bacteria for environmental pollution control [3].

This view aims to summarize the primary application directions of marine microorganisms in environmental protection at present and identify some challenges faced by current research in this field, providing ideas and directions for ecological protection work at the microbial level.

2. Current Applications of Marine Bacteria

2.1 Remediating Heavy Metal Pollution

With industrial development, the natural environment has been polluted by non-biodegradable heavy metals, including zinc, copper, lead, nickel, cadmium, and mercury. Many active groups exist in the cell walls of some marine bacteria, including aldehyde groups (R-CHO), ketone groups (–C=O–), and carboxyl groups (–COOH). Bacteria adsorb heavy metal ions through complexation reactions with these groups or reduce the migration ability and toxicity of heavy metal pollutants by reducing high-valence heavy metals to low-valence ones [4, 5]. In a study, researchers isolated bacteria from the underwater seawater matrix in Bungus Coastal, Padang, and West Sumatra, specifically from moist areas exposed to seawater (rocks, wood, and the lower parts of ships exposed to seawater). Among these, three strains (K4, K5, and K7) capable of producing exopolysaccharides were isolated and applied to remediate metal pollution in aquatic organisms [2].

In addition, there are various extreme environments in the deep sea, including high-temperature, high-pressure, low-temperature, high-pH, and high-salinity environments. Bacteria in these environments possess unique enzymes and strong adaptability, with mechanisms including metal exclusion through permeable barriers and extracellular sequestration via protein-chelator binding, making them highly suitable as catalysts for environmental biotechnology [6]. Moreover, bacteria are small and highly flexible, making them ideal for adsorbing heavy metals in water to remove pollution.

2.2 Degrading Plastic Pollution

Plastic is an artificial high-molecular polymer, usually produced from non-renewable petrochemical products such as petroleum and natural gas. It is widely used commercially due to its low production cost, biological inertness, and light weight. However, plastic waste is difficult to decompose in the natural environment, causing severe pollution. PVC, a commonly used plastic, generates harmful substances during incineration and landfilling, making biological treatment the most suitable method for dealing with PVC waste [7, 8]. There are extensive areas of cold-water regions with constant temperatures in the ocean. Researchers have found that these regions are rich in many extremophiles, including *psychrophilic halophiles, psychrophilic alkaliphiles*, and *psychrophilic halophilic alkaliphiles*. In one experiment, 13 strains capable of degrading PCL were isolated from deep-sea water at a depth of 300 - 600 m [7]. In another study, researchers (Shrikant D. Khandare et al.) successfully isolated 3 marine bacterial strains, and subsequent experiments confirmed that these strains could dechlorinate PVC, reduce its mechanical properties, and increase its hydrophilicity [9].

2.3 Remediating Petroleum Hydrocarbon Pollution

With the extensive use of petroleum in human activities, due to leakage and discharge during ship navigation, offshore oil development, industrial emissions, and other reasons, petroleum hydrocarbons, when discharged into the marine ecosystem, cover the ocean surface, preventing oxygen from entering the water body and causing the death of marine organisms due to hypoxia. At the same time, harmful substances in petroleum are absorbed by marine organisms. Through the food chain, they are transferred and accumulate, having a negative impact on the physiological functions and reproductive capabilities of organisms, and may even lead to species extinction. In such an environment, strains isolated from oil-polluted seawater often have strong tolerance and the potential to decompose petroleum hydrocarbon pollution. Filippo Dell'Anno et al. discovered a unique microbiome in the marine sediments of the Sarno River estuary. From this, two strains, *Alcanivorax xenomutans* strain SRM1 and *Halomonas alkaliantarctica* strain SRM2, with the richest metagenome-assembled genome (MAG) annotations, were identified. Both strains exhibit extremely high degradation rates for petroleum hydrocarbons [10]. Gao et al. conducted a simulation experiment on bioaugmentation to accelerate the bioremediation of oil spills in the ocean. The researchers applied an efficient oil-degrading bacterium (*Pseudomonas aeruginosa* ZS1) to the simulation of bioremediation and obtained a significant increase in the degradation rate of alkanes [11].

2.4 Obtaining Marine Bacteria for Environmental Remediation

Some bacteria found in seawater exhibit strong remediation capabilities for environmental pollution, but are challenging to culture. To solve this complex problem, scientists have employed many methods, including genomics [12], 16S rRNA gene amplification, denaturing gel electrophoresis, etc. [4]. In a sampling study of marine bacterial bio-aggregates with the ability to remediate heavy metal pollution, Ahmed N. Alabssawy et al. found that samples from three different depths contained many bacteria from the *Bacteroidetes* and *Verrucomicrobia* phyla, as well as many unclassified bacterial genera. The composition of these genera was related to temperature and pH [4]. Usually, researchers sample from polluted sediments or different depths of the seawater layer and then use methods such as 16S rRNA gene sequencing, high-throughput sequencing, and genomics to obtain the gene composition of the bacterial community and attempt to isolate and culture strains for subsequent experiments to test their environmental remediation capabilities [10, 13, 14]. Lin et al. used high-throughput culture technology to isolate the marine bacterium SAR202. This bacterium requires dark conditions for cultivation, grows slowly, is sensitive to light, and has an optimal growth temperature of 15-20°C. Genomic analysis revealed that it contains genes encoding archaeal flagella, possibly originating from cross-domain horizontal gene transfer, and has a large number of metabolism-related genes, enabling it to consume sulfated carbohydrates in seawater efficiently. This research offers insights into culturing marine microorganisms, which is of great significance for understanding their ecological roles, addressing environmental challenges, and developing biotechnology products [15].

3. Limitations and Future Prospects

3.1 Limitations

Marine bacteria, as a crucial component of the global ecosystem, hold immense potential in addressing the escalating issue of marine pollution. However, current research and application efforts are confronted with significant challenges, primarily manifesting as technical barriers and difficulties in practical transformation.

3.1.1 Technical Barriers: Difficulty in Isolating and Culturing Microorganisms

The most significant technical hurdle in marine bacteria research is the arduous task of isolating and culturing microorganisms. Statistics indicate that a staggering 99% of marine microorganisms remain unculturable under laboratory conditions to date. This predicament primarily stems from the disconnect between existing cultivation techniques and the real-life marine ecological environment. Traditional isolation and cultivation methods rely on laboratory-simulated environments, which typically set fixed parameters such as temperature, nutrient composition, and physical-chemical conditions. In stark contrast, the marine environment is highly complex and variable. The deep sea is characterized by extreme conditions, including high pressure, low temperatures, and oligotrophy, while coastal waters present unique factors such as fluctuating salinity and variable light levels. For instance, deep-sea piezophilic bacteria are highly dependent on high-pressure environments for growth. Once placed in the normal atmospheric pressure of a laboratory, their cell membrane structures are damaged, and enzyme activities are reduced, rendering normal growth impossible. Some marine nitrogen-fixing bacteria have symbiotic relationships with algae. Without their symbiotic partners, they struggle to obtain the special metabolites necessary for growth, making it difficult to culture them independently. Additionally, research on the pollutant degradation mechanisms of marine bacteria is mainly confined to single strains or simple systems. The lack of a systematic understanding of the collaborative metabolic networks among bacteria in complex ecosystems means it is challenging to establish culture systems that can support the co-growth of multiple bacteria, further intensifying the difficulty of isolation and cultivation.

3.1.2 Difficulties in Practical Transformation

Translating laboratory research findings related to marine bacteria into practical engineering applications is also challenging. In the natural environment, marine bacteria are exposed to complex ecological conditions and environmental pressures, resulting in uncertainties regarding their survival, stability, and tolerance to various pollutants. Take, for example, strains that demonstrate excellent capabilities for degrading petroleum hydrocarbons in the laboratory. When introduced into actual marine oil-polluted areas, their degradation efficiency drops significantly due to drastic changes in seawater salinity, temperature, and the competitive effects of other microorganisms. Moreover, the bioremediation process may trigger unpredictable ecological chain reactions. If introduced, marine bacteria that multiply excessively may disrupt the balance of the original ecosystem and have negative impacts on other marine organisms. In addition, large-scale application of bioremediation technology faces an efficiency bottleneck. For the treatment of plastic pollutants, although some extremophiles possess degradation abilities, it is challenging in practical large-scale applications to ensure stable and efficient treatment results. Currently, there is a lack of mature technical means to optimize the metabolic pathways of bacteria and enhance their environmental adaptability, making it difficult to bridge the gap between laboratory research and practical engineering applications. As a result, many promising research results fail to be effectively utilized in real-world scenarios.

3.2 Future Directions

Future research should focus on technological innovation and theoretical breakthroughs. Marine microbial research and application are of far-reaching significance for marine ecological protection and sustainable development. However, it is currently confronted with numerous challenges, such as difficulties in cultivation and obstacles to promotion. To break through these bottlenecks, a series of technical means can be employed.

In terms of the isolation and cultivation of microorganisms, microfluidic chip technology plays a vital role. It can precisely manipulate fluids within tiny channels, simulating the complex microenvironments in the ocean and providing microorganisms with a living space that is close to nature. By accurately adjusting parameters such as nutrient concentration, oxygen content, and fluid shear force, for example, by creating a gradient nutrient environment, marine microorganisms with specialized nutritional requirements can be isolated. Meanwhile, microfluidic chips can also achieve the isolation and cultivation of single cells, avoiding competition and mutual inhibition among microorganisms, which helps to discover and cultivate rare microorganisms that are easily overlooked by traditional methods.

In-situ cultivation devices are equally significant. This technology places the cultivation devices directly into the marine environment, allowing microorganisms to grow in their native environment and preserving physical and chemical conditions such as deep-sea high pressure and low temperature to the greatest extent. For instance, deep-sea in-situ cultivation devices can capture piezophilic and psychrophilic bacteria that rely on the unique deep-sea environment for survival, solving the problem of difficult cultivation caused by the large difference between the laboratory-simulated environment and the real marine environment. In addition, although metagenomics is not a direct cultivation technology, it can analyze all the genes of microorganisms in environmental samples. Through metagenomic sequencing, we can identify the types of microorganisms and obtain functional gene information, explore the metabolic pathways and specialized functions of unknown microorganisms, and subsequently optimize cultivation conditions, thereby improving the success rate of isolating and cultivating specific microorganisms.

Regarding the promotion and application of synthetic biology technology, it can be used to transform marine bacteria through gene editing and metabolic engineering. By knocking out or enhancing specific genes, marine bacteria can be endowed with stronger pollutant-degradation capabilities, improving the decomposition efficiency of pollutants such as petroleum hydrocarbons and plastics. At the same time, optimizing the metabolic pathways of bacteria can enhance their survival and adaptability in complex environments, promoting the large-scale application of bioremediation technology.

4. Conclusion

This paper systematically examines the potential of marine bacteria in bioremediating marine pollutants, highlighting their mechanisms and current research landscape. The marine ecosystem, as a key player in global geochemical cycles, has been increasingly threatened by pollutants like heavy metals, plastics, and petroleum hydrocarbons since the Industrial Revolution. Marine bacteria, adapted to extreme marine environments (e.g., high pressure, low temperature), exhibit unique degradation capabilities, making them promising candidates for environmental cleanup.

For heavy metal pollution, marine bacteria leverage cell wall functional groups (e.g., carboxyl, aldehyde) for adsorption or reduce metal valence to mitigate toxicity. In plastic degradation, extremophiles (e.g., psychrophilic halophiles) isolated from deep-sea cold waters can dechlorinate PVC and decompose polyesters, as observed in strains such as those identified by Khandare et al. For petroleum hydrocarbons, strains such as *Alcanivorax xenomutans* SRM1 and *Pseudomonas aeruginosa* ZS1 demonstrate high degradation efficiency, breaking down alkanes and restoring marine oxygen levels.

However, research faces critical hurdles: over 99% of marine bacteria remain unculturable due to mismatches between laboratory conditions and their natural habitats (e.g., high pressure in the deep sea, symbiotic dependencies). Practical application is further challenged by ecological uncertainties, such as reduced degradation efficiency in variable seawater conditions and potential ecosystem disruptions.

Future directions advocate for technological innovations, including microfluidic chips for simulating marine microenvironments, in situ cultivation devices to preserve native conditions, metagenomics for the discovery of functional genes, and synthetic biology to engineer bacteria for enhanced pollutant tolerance. These approaches aim to bridge the gap between lab research and large-scale bioremediation, fostering sustainable marine environmental protection.

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