Strengthening Electromicrobiology Research for Sustainable Utilization of Novel Microbial Resources from Coastal Zones: Postprint

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Abstract

The development and utilization of coastal zone biological resources, particularly the sustainable utilization of novel microbial strategic resources, constitutes an important component of China' s ecological civilization construction and a critical underpinning for the sustainable development of China' s coastal economy. This article provides a brief review of the development trends and frontier scientific issues in the discipline of electromicrobiology, and offers prospects for its future development directions. The article proposes that sustainable development of coastal zones requires synergistic development across multiple disciplines, necessitating enhanced cultivation of interdisciplinary talents and international cooperation, strengthened collaboration with government and enterprises at the application level, deployment of key research projects and organization of large-scale scientific research programs at the national/international level in basic research, and even the establishment of interdisciplinary research centers centered on "coastal science" . Strengthening research in electromicrobiology facilitates the utilization of novel microbial strategic resources, contributes to the sustainable development of China' s coastal economy, and supports ecological civilization construction.

Full Text

Preamble: Coastal Science and Sustainable Development

Strengthening Electromicrobiology Research and Sustainable Utilization of Novel Microbial Strategic Resources in Coastal Zones

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Abstract

The exploitation and utilization of biological resources in coastal zones, particularly the sustainable use of novel microbial strategic resources, constitutes a vital component of China's ecological civilization construction and a key pillar for sustainable coastal economic development. This paper briefly reviews the development trends and frontier scientific issues in electromicrobiology and prospects future research directions. We argue that sustainable coastal development requires multidisciplinary synergy, strengthened cultivation of interdisciplinary talent, and enhanced international cooperation. At the application level, collaboration with government and industry must be intensified, while at the basic research level, key projects should be deployed and large-scale national/international research initiatives organized, potentially culminating in the establishment of an interdisciplinary research center focused on "Coastal Science." Strengthening electromicrobiology research will facilitate the utilization of novel microbial strategic resources, contribute to sustainable economic development in China's coastal zones, and support ecological civilization construction.

Keywords: coastal zone ecological civilization, sustainable utilization of coastal zone resources, novel microbial strategic resources, electromicrobiology, sustainable development

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The 18th National Congress of the Communist Party of China explicitly called for "vigorously promoting ecological civilization construction," a crucial component of socialism with Chinese characteristics that affects public welfare, national future, and the realization of the "Two Centenary Goals" and the Chinese Dream of national rejuvenation. A key task in ecological civilization construction is enhancing sustainable development capacity, which forms the foundation for rational, moderate exploitation of coastal resources and comprehensive management of coastal environmental security.

However, with the implementation of China's coastal development strategies, particularly the rapid expansion of artificial reclamation, typical coastal habitats are being or have already been severely damaged, placing immense pressure on coastal biodiversity and ecosystem health. The scope and intensity of land-based pollution, seawater intrusion, and coastal erosion continue to increase, significantly altering the distribution patterns of coastal biological resources. This not only impacts traditional industries such as agriculture and fails to support strategic emerging industries like bio-industry, but also poses severe challenges to ecosystem health and affects the sustainable development of coastal environments that underpin the blue economy. Therefore, against the backdrop of intensive human activities and global climate change, the sustainable utilization of novel microbial strategic resources that can improve and restore coastal environments represents both a major scientific question and an urgent national need.

Electricigens represent precisely such a novel class of microbial strategic resources. These microorganisms possess the ability to perform extracellular respiration under anaerobic conditions, enabling them to effectively recover energy (such as electricity, methane, and hydrogen) and resources while simultaneously treating wastewater and remediating environmental pollution. The discovery of Electricigens has facilitated the development of Microbial Fuel Cell (MFC) and Microbial Electrosynthesis (ME) technologies, endowing them with broad application value and prospects. MFC technology employs microorganisms as catalysts to convert chemical energy into electrical energy. Electricigens perform electrogenic respiration in the anode chamber, decomposing organic matter under anaerobic conditions to produce carbon dioxide while transferring electrons to the anode, which then travel through an external circuit to electron acceptors in the cathode. This technology can be applied not only to environmental remediation of pollutants [4], heavy metal degradation [5,6], organic wastewater treatment [7,8], and biosensors [9], but also generates electricity. Microbial electrosynthesis technology (Fig. 1 [Figure 1: see original paper]) is a novel semi-artificial photosynthesis simulation developed based on discoveries in electromicrobiology. Its fundamental principle involves Electricigens directly acquiring (photo)electrons generated from solar energy via electrodes to reduce carbon dioxide and produce high-value biochemical or energy substances such as acetate, formate, and even butanol [10-13].

This paper, building upon domestic and international electromicrobiology research, elaborates on research progress and the necessity of conducting related studies in coastal zones from four perspectives: the definition of electromicrobiology, coastal electromicrobiology research and biological resource utilization, development trends in global electromicrobiology research, and recommendations for strengthening research and development of coastal electromicrobial resources in China, thereby promoting the rapid development of electromicrobiology in China.

1. Definition, Connotation, and Significance of Electromicrobiology

Electromicrobiology is an emerging discipline that studies Electricigens, representing an interdisciplinary field combining microbiology and electrochemistry. Its research scope encompasses life sciences, chemistry, earth sciences, and engineering and materials sciences, with the core mission of elucidating microbial extracellular electron transfer mechanisms and exploring their application prospects in sustainable development fields such as environmental protection, pollution control, and new energy development. In recent years, an increasing number of Electricigens have been discovered across both eukaryotic and prokaryotic microorganisms, including bacteria and archaea. Most reported Electricigens are bacteria distributed among Proteobacteria, Firmicutes, Acidobacteria, and Actinobacteria phyla, with the majority concentrated in different subclasses of Proteobacteria exhibiting varying electrogenic capabilities.

Representative strains include *Shewanella* sp. from Gammaproteobacteria and *Geobacter* sp. from Deltaproteobacteria, both belonging to dissimilatory iron-reducing bacteria [2,3].

The discovery of Electricigens has advanced Microbial Fuel Cell (MFC) technology, which uses microorganisms as catalysts to convert chemical energy into electricity. Electricigens perform electrogenic respiration in the anode chamber, decomposing organic matter under anaerobic conditions to produce CO while transferring electrons to the anode, which then flow through an external circuit to electron acceptors in the cathode. This technology can be applied to environmental remediation of pollutants [4], heavy metal degradation [5,6], organic wastewater treatment [7,8], biosensors [9], and electricity generation. Microbial electrosynthesis technology (Fig. 1 [Figure 1: see original paper]) is a novel semi-artificial photosynthesis simulation developed based on discoveries in electromicrobiology. Its fundamental principle involves Electricigens directly acquiring (photo)electrons generated from solar energy via electrodes to reduce carbon dioxide and produce high-value biochemical or energy substances such as acetate, formate, and even butanol [10-13].

2. Coastal Zone Electromicrobiology Research and Biological Resource Utilization

Coastal zones are the interface and transition zone between land and sea, representing complex and overlapping geographic units characterized by abundant resources, prominent location advantages, ecological vulnerability, and frequent disasters. With the convergence of land and marine economies, coastal zones have become "golden areas" in the socioeconomic domain through bidirectional radiation of productivity, hosting the most active and concentrated human activities. Currently, nearly 60% of the world' s population lives in coastal zones that account for only 10% of Earth' s land area. However, rapid population growth and urbanization have subjected coastal zones to enormous pressures from global climate change, sea-level rise, ecological destruction, biodiversity loss, intensifying pollution, and fishery resource degradation, severely affecting sustainable development. Sustainable utilization of coastal biological resources is therefore crucial for promoting ecological civilization construction.

Traditional microbial resource exploitation has focused on developing abundant microbial secondary metabolites to address major diseases threatening human health, such as malignant tumors, diabetes, and AIDS. Research by Nielsen' s team at Aarhus University discovered that a novel species of Desulfobulbaceae bacteria in marine sediment anaerobic environments can form filaments connecting anaerobic and aerobic zones, enabling bacteria in anaerobic zones to extract electrons from hydrogen sulfide and transfer them to oxygen in aerobic zones, thereby forming "underwater cables" [14,15]. This provides direct evidence for the existence of electrogenic bacteria in marine environments, highlighting the research and application value of electrogenic microorganisms as a novel strategic resource in coastal zones. Although current research on Electricigens in coastal zones remains limited, their importance in coastal biogeochemical cycling, bioenergy, environmental pollution remediation, and biofilm corrosion prevention is increasingly recognized.

In terms of material cycling, coastal ecosystems represent important extensions of terrestrial ecosystems and key components of coastal zones, serving as critical links between terrestrial and marine carbon pools. Distributed in estuaries, tidal flats, and coastal wetlands, coastal ecosystems exhibit primary characteristics, fragility, rarity, and unique dual land-sea attributes, forming the most frequently interactive and active ecological transition zones with human activities [16]. Coastal rivers flow along channels, influenced by both regional geomorphological features, anthropogenic factors, and marine-land interactions. Coastal rivers and their sediments possess aerobic, anaerobic, and alternating aerobic-anaerobic zones where microbial redox processes occur extensively. Microorganisms form functional groups including aerobic respiring bacteria, nitrate-reducing bacteria, sulfate-reducing bacteria, methanogenic archaea, ammonia-oxidizing bacteria, and iron-reducing bacteria, utilizing various electron acceptors (O , NO , Fe(III), SO ^{2} , and CO) for respiration while playing important roles in pollutant degradation, endowing coastal rivers with considerable self-purification and pollution tolerance capacities. Coastal wetlands, simultaneously influenced by terrestrial and marine interactions and experiencing repeated inundation-drainage processes, provide ideal environments for studying redox reactions and coupled cycling of biogenic elements such as carbon, iron, and sulfur driven by Electricigens, which play pivotal roles in global climate change processes.

Marine sediment microbial fuel cells represent important applications of Electricigens in marine and coastal environments. By burying the anode in seafloor sediments and placing the cathode in overlying seawater, abundant organic matter in sediments serves as fuel while dissolved oxygen in seawater acts as the oxidant, with microorganisms in seafloor sediments serving as biocatalysts for current output [17-19]. Connecting the anode and cathode through an external circuit yields low-level electrical energy. Due to advantages including maintenance-free operation, continuous supply, abundant substrates, low internal resistance, environmental friendliness, and low cost, these devices show promise as power sources for low-power environmental monitoring instruments measuring temperature, salinity, and humidity in marine environments. Although not yet commercially applied, they are attracting increasing attention. Based on this principle, various sediment and activated sludge microbial fuel cells have been constructed to generate electricity while degrading organic pollutants for environmental remediation.

Regarding biofilm research, conventional wisdom holds that biofilms formed by microbial attachment on marine artificial structures cause severe fouling and corrosion, resulting in enormous economic losses. However, the discovery of electroactive biofilms capable of receiving or producing electrons reveals that their positive impacts may far outweigh negative effects if properly utilized.

Most electroactive bacteria originate from seawater, marine environments, and wastewater [20]. Mansfeld and Nagiub [21] first proposed the concept of "using renewable biofilms for corrosion control," where certain bacteria form biofilms on metal surfaces and produce metabolites that act as corrosion inhibitors, shifting the corrosion potential to suppress corrosion. This endows electroactive biofilms with tremendous potential for marine corrosion prevention and control.

Additional applications of coastal Electricigens include in-situ remediation of soil or groundwater pollution, degradation of marine oil pollution using seafloor sediment microbial fuel cells, and investigation of marine biogeochemical processes. Thus, MFC research holds underestimated potential across multiple directions, and Electricigens represent a unique coastal strategic biological resource with broad application prospects.

3. Development Trends in Global Electromicrobiology Research

To further understand development trends in electromicrobiology research, we conducted a Web of Science database analysis (Fig. 2 [Figure 2: see original paper]). Since the first electrogenic microorganism with extracellular electron transfer capability, *Geobacter metallireducens*, was reported in *Nature* in 1987, publications in this field have steadily increased. Building upon 20 years of accumulation from 1987-2006, the period 2007-2011 showed accelerated growth, with the subsequent five years continuing this rapid increase—powerful evidence for the field' s vigorous development over the past decade.

Further analysis of publication distribution across journals reveals numerous papers in top-tier academic journals (Fig. 3 [Figure 3: see original paper]), including 11 in *Nature*, 10 in *Science*, 17 in *PNAS*, and 20 in *Nature* subjournals. Additionally, dozens of articles appear in leading specialized journals such as *Energy & Environmental Science* (33), *ISME Journal* (22), *Environmental Microbiology* (24), and *Applied and Environmental Microbiology* (86). This demonstrates that electromicrobiology represents a hot research topic attracting worldwide scientific attention.

To reveal China' s contribution to electromicrobiology development, we analyzed these papers by country (Fig. 4 [Figure 4: see original paper]). The United States holds absolute dominance in publication numbers. China ranks second among the 12 surveyed countries with strong research capacity, indicating considerable research strength, though still far behind the US with less than half the publication output.

4. Recommendations for Strengthening Research and Development of Coastal Electromicrobial Resources in China

China has vast maritime territories spanning tropical, subtropical, and temperate zones across more than 32,000 km of coastline, including over 18,000 km of mainland shoreline. The adjacent Bohai, Yellow, East China, and South China Seas cover more than 4.7 million km^2, with major rivers including the Yalu, Liao, Haihe, Yellow, Huaihe, Yangtze, Qiantang, Min, and Pearl Rivers [22]. China' s extensive continental shelves and rich coastal landforms make coastal zones among the most biologically productive marine areas and crucial venues for human survival and economic development, while providing excellent bases for developing electrogenic microbial resources.

In early 2016, a *Science* commentary titled "A new diet for methane oxidizers" [23] highlighted two *Nature* articles and one *Science* article, suggesting that a nearly 40-year-old mystery was about to be solved. The commentary noted that anaerobic methanotrophic archaea were found to form aggregates coupled with sulfate-reducing bacteria, yet pure cultivation remained elusive, likely because interspecies direct electron transfer was required. Based on this important discovery, Scheller et al. [24] used stable isotope tracing and other techniques to demonstrate that artificial electron acceptors could decouple this long-standing relationship, enabling pure cultivation—another important application of interspecies direct electron transfer theory. Coastal environments are likely to become crucial frontiers for advancing such cutting-edge scientific research.

Microbial extracellular respiration may represent the primary metabolic pathway of early Earth microorganisms, with extracellular electron transfer mechanisms being the core scientific question in microbe-organic matter-mineral interactions. Discovered mechanisms mainly include electron shuttling, nanowire conduction, and outer membrane redox protein mediation [25-30]. Coastal wetlands theoretically represent "golden zones" for studying microbial extracellular electron transfer, yet in-situ research on microbial extracellular electron transfer in coastal zones or coastal wetlands remains rare. Therefore, research on microbial extracellular electron transfer in coastal zones is urgently needed, as it can provide theoretical foundations and technical pathways for sustainable development of China' s ecological environment.

We recommend leveraging special funding and programs such as the National Natural Science Foundation' s "Excellent Young Scientists" and "Distinguished Young Scientists" to strengthen talent pipeline development, construct electrogenic microbial resource libraries, develop biogeochemical cycling databases and quantitative models, cultivate interdisciplinary talent, and enhance international cooperation. At the application level, collaboration with government and enterprises should be strengthened, while at the basic research level, key projects should be deployed and large-scale national/international research programs organized, potentially establishing a "Coastal Science" -focused interdisciplinary research center. Strengthening electromicrobiology research will facilitate utilization of novel microbial strategic resources, promote sustainable economic development in China' s coastal zones, and advance ecological civilization construction.

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"Two Hundred Talents Program." His research focuses on mechanisms of microbial extracellular electron transfer, with major achievements including: supporting the theory of direct interspecies electron transfer (DIET) between bacteria and methanogenic archaea; revealing a novel pathway of indirect methane production from acetate and related microorganisms; identifying a new cluster of carbon dioxide-fixing microorganisms; and demonstrating that conductive granular activated carbon and magnetite nanoparticles can promote direct electron transfer among iron(III)-reducing bacteria, revealing the mechanism by which magnetite nanoparticles compensate for c-type cytochrome function.
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Note: Figure translations are in progress. See original paper for figures.