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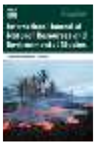

# Ethical Considerations in the Application of Enzyme-Induced Calcium Carbonate Precipitation (EICP) for Soil Improvement

Xu Guo*

Institute of Resource and Environment, Henan Polytechnic University, Jiaozuo, Henan 454000, China

*Corresponding Author: Xu Guo(1454766866@qq.com)

## ABSTRACT

This paper systematically explores the application of enzyme-induced calcium carbonate precipitation (EICP) technology in soil improvement, along with its associated ethical considerations. First, the fundamental principles of EICP are described, wherein urease catalyzes the hydrolysis of urea to produce calcium carbonate precipitates, thereby enhancing soil structure and stability. Next, the wide-ranging applications of EICP in soil reinforcement, foundation treatment, and pollution remediation are analyzed, highlighting its notable technical advantages such as environmental friendliness, low energy consumption, and operational simplicity. However, the technology also faces several challenges, including difficulties in reaction control, uncertainty regarding long-term effectiveness, and cost-related concerns. The paper further provides a comprehensive analysis of the ethical issues surrounding EICP from three perspectives: environmental ethics, social ethics, and economic ethics. From an environmental ethics perspective, the potential impacts of EICP on ecosystems and the broader environment, as well as its sustainability, are discussed. In terms of social ethics, the discussion emphasizes the social responsibilities involved in the promotion and application of the technology, along with the rights and interests of stakeholders. From an economic ethics standpoint, the paper conducts a cost-benefit analysis and examines issues of fairness in the application of the technology.

## KEYWORDS

Enzyme-Induced Calcium Carbonate Precipitation (EICP); Soil Improvement; Environmental Ethics; Technological Applications; Sustainable Development.

## 1. INTRODUCTION

Enzyme-Induced Carbonate Precipitation (EICP) is a technique that utilizes biocatalytic reactions to induce the formation of calcium carbonate precipitates. The underlying mechanism involves the urease-catalyzed hydrolysis of urea, which produces ammonia and carbonate ions. These ions subsequently react with calcium ions in solution to form calcium carbonate precipitates. This process has attracted considerable attention in biogeological research and has demonstrated promising applications in soil improvement and environmental remediation. The significance of EICP in soil stabilization is increasingly recognized. Conventional soil improvement methods, such as mechanical reinforcement and chemical treatments, are often associated with high energy consumption, elevated costs, and adverse environmental impacts. In contrast, EICP, as an emerging biotechnological approach, offers a sustainable alternative due to its low energy requirements and environmentally friendly characteristics [1].However, the growing application of EICP also raises emerging ethical concerns. First, the long-term environmental consequences of EICP remain unclear, and large-scale application may pose potential risks to ecosystems. Second, the implementation and dissemination of this technology involve multiple stakeholders, requiring careful consideration of fairness and equitable resource allocation. Furthermore, balancing the cost and benefits of EICP is another critical issue. Therefore, ethical considerations are essential to guide the responsible application of EICP in soil improvement practices.

## 2. OVERVIEW OF ENZYME-INDUCED CALCIUM CARBONATE PRECIPITATION (EICP) TECHNOLOGY

### 2.1. Principle of EICP

Enzyme-Induced Carbonate Precipitation (EICP) is a biochemical technique used to produce calcium carbonate ($CaCO_3$) through enzymatic reactions. The core mechanism involves the use of urease to catalyze the hydrolysis of urea ($CO(NH_2)_2$). The specific chemical reactions involved are as follows:

Urease catalyzes the hydrolysis of urea to produce ammonia (NH3) and carbon dioxide (CO2).

$$CO(NH_2)_2 + 2H_2O \xrightarrow{urease} 2NH_3 + CO_2 . \tag{1}$$

Ammonia dissolves in water to form ammonium hydroxide (NH4OH).

$$NH_3 + H_2O \rightleftarrows NH_4OH . \tag{2}$$

Ammonium hydroxide dissociates into ammonium ions (NH+ 4) and hydroxide ions ($OH^-$).

$$NH_4OH \rightleftarrows NH_4^+ + OH^- . \tag{3}$$

Carbonic acid in water forms bicarbonate ions ($HCO3^-$) and hydroxide ions ($OH^-$).

$$CO_2 + H_2O \rightleftarrows H_2CO_3 \rightleftarrows HCO_3^- + H^+ \rightleftarrows CO_3^{2-} + 2H^+ . \tag{4}$$

Ultimately, carbonate ions combine with calcium ions (Ca2+) in the solution to form calcium carbonate precipitate.

$$Ca^{2+} + CO_3^{2-} \longrightarrow CaCO_3 \downarrow . \tag{5}$$

This chemical and biological process, driven by a series of enzyme-catalyzed reactions, leads to the formation of stable calcium carbonate precipitates, which contribute to soil reinforcement and improvement.

### 2.2. Application fields of EICP

Soil reinforcement: The application of EICP technology in soil reinforcement primarily enhances the shear strength and bearing capacity of the soil. By introducing urease and calcium sources into the soil, calcium carbonate precipitates form between soil particles, thereby increasing soil stability. This method is particularly suitable for sandy soils, loose deposits, and other geological conditions requiring stabilization.

Foundation treatment: In foundation engineering, EICP technology can be used to enhance the bearing capacity of foundation soils and reduce settlement. It offers significant advantages in treating soft soils and liquefiable ground, effectively improving foundation stability and safety. For example, in building and road construction, EICP can be applied as a pre-treatment method to strengthen the load-bearing capacity of foundations.

Pollution remediation: The application of EICP technology in the remediation of contaminated soils has also attracted considerable attention. By inducing calcium carbonate precipitation, harmful substances such as heavy metals can be immobilized in the soil, reducing their mobility and spread, and thereby lowering the risk of environmental pollution [2]. This method is not only environmentally friendly but also relatively cost-effective, offering promising potential for widespread application.

## 3. SPECIFIC APPLICATIONS OF EICP IN SOIL IMPROVEMENT

### 3.1. Soil structure improvement

Enzyme-Induced Calcium Carbonate Precipitation (EICP) has shown significant effectiveness in improving soil structure. By forming calcium carbonate precipitates between soil particles, EICP can substantially enhance the physical structure of the soil, increasing its stability and shear strength. This improvement is primarily achieved through the following mechanisms:

1. Enhancing inter-particle bonding: The calcium carbonate precipitates produced by EICP act as a binding agent between soil particles, increasing inter-particle cohesion and thereby improving the soil's shear strength. This effect is particularly beneficial for reinforcing sandy soils and loose sediment layers.
2. Reducing soil porosity: Calcium carbonate precipitates fill the voids within the soil, thereby reducing its porosity and increasing its compaction. This improvement enhances the soil's load-bearing capacity and overall stability, helping to prevent soil collapse and foundation settlement [3].
3. Improving soil erosion resistance: Calcium carbonate precipitates form a protective layer on the soil surface, enhancing its resistance to erosion and reducing the risks of wind and water erosion. This is especially effective in coastal and arid regions, where EICP technology can significantly prevent soil degradation and loss.

### 3.2. Foundation reinforcement

The application of EICP technology in foundation reinforcement has also received widespread attention. Foundations serve as critical supports for buildings and infrastructure, with their stability and bearing capacity directly impacting the safety and durability of engineering structures. Reinforcing foundations using EICP can significantly enhance the performance of foundation soils.

#### 3.2.1. Related Cases:

1) Foundation reinforcement project for a high-rise building in China: In this project, EICP technology was applied to strengthen the foundation soil. The results showed a 30% increase in shear strength, a significant enhancement in bearing capacity, and effective control of foundation

settlement.

2) Highway expansion project in the United States: In this project, EICP technology was employed to treat soft foundation soils. After construction, the soil compaction and stability were significantly improved, ensuring the highway's bearing capacity and safety.

### 3.2.2. Performance Analysis:

1) Enhancement of foundation bearing capacity: EICP technology improves the bearing capacity of foundations by increasing the shear strength and compaction of foundation soils, effectively supporting the superstructure and reducing settlement and deformation.
2) Improvement of foundation stability: The calcium carbonate precipitates produced by EICP form stable structures within the foundation soil, enhancing overall foundation stability and reducing the risk of failure.
3) Reduction of construction costs: Compared to traditional foundation reinforcement methods, EICP technology offers advantages such as low energy consumption and cost-effectiveness, enabling cost reduction while ensuring project quality [4].

## 3.3. Environmental remediation

EICP technology holds great potential in environmental remediation, especially in the remediation of contaminated soils where it offers significant advantages. By generating calcium carbonate precipitates, pollutants in the soil can be immobilized, reducing their mobility and spread, thereby achieving the goals of environmental remediation.

### 3.3.1. Related Cases:

1) Heavy metal pollution remediation: In an industrial area in China, long-term industrial emissions have caused severe heavy metal contamination in the soil. After treatment with EICP technology, heavy metals in the soil were effectively immobilized, reducing their impact on the surrounding environment. Experimental results showed a significant decrease in the bioavailability of heavy metals in the soil, leading to environmental improvement.
2) Organic pollutant remediation: In an agricultural area in the United States, soil contamination by organic pollutants such as pesticides and organic solvents exceeded acceptable levels. Treatment with EICP technology resulted in calcium carbonate precipitates binding with these pollutants, reducing their mobility and toxicity in the soil. After treatment, the concentration of organic pollutants in the soil significantly decreased, restoring the farmland environment.

### 3.3.2. Performance Analysis:

1) Immobilization of pollutants: Calcium carbonate precipitates produced by EICP technology can immobilize heavy metals and organic pollutants in the soil, reducing their migration and diffusion, thereby lowering environmental risks.
2) Reduction of pollutant bioavailability: Treatment with EICP technology significantly decreases the bioavailability of pollutants, thereby reducing risks to flora, fauna, and human health [5].
3) Environmentally friendly and efficient: EICP technology is eco-friendly and efficient, producing no secondary pollution and enabling soil remediation without damaging soil structure or the surrounding ecosystem.

# 4. ETHICAL CONSIDERATIONS OF EICP TECHNOLOGY

## 4.1. Environmental Ethics

### 4.1.1. Environmental Impact of EICP Technology

Although Enzyme-Induced Calcium Carbonate Precipitation (EICP) technology offers clear advantages in soil improvement and environmental remediation, its potential impacts on ecosystems and the environment must be carefully considered. By altering the physical and chemical properties of soil through calcium carbonate precipitation, EICP may affect soil microbial communities, plant growth, and surrounding ecosystems.

The calcium carbonate precipitates formed through EICP in soil can alter the soil's pore structure and permeability, potentially disrupting the habitat and activity patterns of soil microorganisms. Microorganisms play a crucial role in soil ecosystems, and changes in their population size and diversity can have profound effects on soil health and ecosystem stability. Excessive calcium carbonate accumulation may lead to soil hardening, hindering root development and the absorption of water and nutrients, thereby negatively impacting plant growth and crop yield [6].

Large-scale application of EICP technology may have certain impacts on surrounding surface water and groundwater systems. The migration and diffusion of calcium carbonate precipitates in the soil could result in the release of calcium and carbonate ions into nearby water bodies, altering their chemical composition and potentially affecting aquatic organisms and water quality.

### 4.1.2. Sustainability of EICP Technology Applications

Despite its potential environmental impacts, EICP technology also offers notable advantages in terms of sustainability. Compared to traditional soil improvement and environmental remediation methods, EICP is characterized by low energy consumption and the use of widely available materials, making it more sustainable. With proper control and optimization of its application, EICP can achieve soil improvement and environmental restoration goals while minimizing negative environmental effects.

EICP technology relies on biological enzymes and natural chemical reactions, producing no harmful byproducts and thus meeting environmental protection standards. The resulting calcium carbonate precipitates are stable and durable, resistant to hydrolysis and decomposition, and capable of maintaining soil improvement effects over the long term. Moreover, EICP has demonstrated excellent performance in immobilizing heavy metals and organic pollutants, effectively reducing environmental contamination and supporting ecosystem health.

In conclusion, the ethical application of EICP technology requires a balanced consideration of its potential environmental impacts and sustainability. By applying and optimizing the technology responsibly, it is possible to achieve the dual goals of environmental protection and sustainable development [7].

## 4.2. Social Ethics

### 4.2.1. Promotion and Application of EICP Technology

EICP technology carries significant social responsibility in its promotion and practical application. As an emerging soil improvement and environmental remediation technique, its dissemination and adoption require not only technical feasibility but also social recognition and support. During the promotion process, emphasis should be placed on public education to raise awareness and acceptance of EICP technology while ensuring its safety and reliability.

In practical applications, strict adherence to technical specifications and operational standards is essential to ensure the scientific validity and rationality of EICP technology, preventing environmental issues and social conflicts caused by improper operation or technical errors

[8].Moreover, during the promotion and application process, it is important to consider the specific conditions of different regions and application scenarios, adapting and optimizing technical solutions accordingly to achieve the best possible outcomes.Stakeholders in the Application of EICP Technology.

The application of EICP technology involves multiple stakeholders, including farmers, landowners, government agencies, and research institutions. During the implementation process, it is necessary to comprehensively consider the interests of all parties and balance the needs and expectations of different stakeholders.

For farmers and landowners, EICP technology can significantly enhance soil productivity and foundation stability, thereby increasing crop yields and land value. However, the potential costs and risks during the application process must also be carefully considered and assessed to ensure the technology's economic feasibility and sustainability [9].

The government plays a crucial role in the promotion and application of EICP technology by formulating relevant policies and regulations, providing technical support and funding, and facilitating the standardized and regulated development of the technology. Research institutions play a key role in technology development and optimization by continuously conducting research and experiments to enhance the performance and applicability of EICP technology, thereby providing a solid scientific basis for its widespread adoption.

## 4.3. Economic Ethics

### 4.3.1. Cost-Benefit Analysis of the Application of EICP Technology

The economic benefits and costs of EICP technology are key factors in assessing its feasibility and potential for broader application. Its cost-effectiveness varies across different application scenarios. Overall, EICP offers advantages such as low energy consumption and low material costs, making it particularly suitable for large-scale soil improvement and environmental remediation projects, where it can significantly reduce total expenditures.

In practical applications, a detailed analysis of the cost-effectiveness of EICP technology is required, taking into account both the direct implementation costs and long-term benefits [10]. For example, in foundation reinforcement projects, although the initial investment in EICP may be relatively high, its ability to significantly enhance foundation stability and load-bearing capacity can reduce the need for future maintenance and repair, thereby improving overall economic efficiency.

### 4.3.2. Equity in the Application of EICP Technology

The promotion and application of EICP technology also raise issues of resource allocation and equity. The distribution of technological resources and funding should emphasize fairness and justice, ensuring that different regions and populations can benefit from the development and implementation of the technology. In particular, economically underdeveloped areas should be provided with appropriate technical support and financial assistance to facilitate the widespread adoption of EICP, thereby promoting sustainable economic and environmental development in those regions.

During the implementation of the technology, it is essential to fully respect and safeguard the rights and interests of local communities and stakeholders. Ensuring transparency and openness in the application process, along with participatory decision-making and benefit-sharing mechanisms, is critical to achieving equity and sustainability in the use of the technology.

In summary, the development and application of EICP technology require comprehensive consideration and coordination of environmental, social, and economic ethical dimensions. Through rigorous scientific research and responsible implementation, it is possible to achieve a harmonious integration of technological advancement and sustainable societal development.

# 5. CASE STUDY

## 5.1. Successful Cases at Home and Abroad

### 5.1.1. Foundation Reinforcement Project for a High-Rise Building in China

In a high-rise building foundation reinforcement project in China, EICP technology was employed to treat soft soil foundations to improve their load-bearing capacity and stability. By injecting a solution containing urease and calcium sources into the foundation soil, calcium carbonate precipitation was successfully induced, significantly enhancing the soil's shear strength. The results showed a 30% increase in shear strength of the foundation soil, effective control of foundation settlement, and ensured the safety of the building.

Ethical Analysis: This project demonstrated the significant potential of EICP technology in foundation reinforcement. During implementation, strict technical standards and environmental protection measures were followed to ensure the safety and reliability of the technology. Furthermore, the project team collaborated closely with local government and communities, fully considering stakeholders' needs to achieve both social and economic benefits from the technology's application [11].

### 5.1.2. Highway Expansion Project in the United States

In a highway expansion project in the United States, EICP technology was applied to treat soft soil foundations along the route to enhance the road's load-bearing capacity and stability. Following EICP treatment, the compaction and stability of the foundation soil were significantly improved, ensuring the highway's structural integrity and safety. Upon completion, the service life and safety of the roadway were substantially extended, resulting in reduced maintenance costs over time.

Ethical Analysis: This project fully demonstrated the application prospects of EICP technology in large-scale soil improvement projects. Throughout the promotion and implementation phases,the project team emphasized environmental protection and sustainability, thereby avoiding secondary environmental pollution. Additionally,comprehensive environmental impact assessments and public consultations were conducted prior to implementation to ensure transparency and fairness in the application of the technology.

## 5.2. Failure Cases and Lessons Learned

### 5.2.1. Heavy Metal Contamination Remediation Project in an Agricultural Area

In a heavy metal contamination remediation project in an agricultural area, EICP technology was applied to immobilize heavy metals in the soil. However, due to insufficient precision in controlling technical parameters during implementation, calcium carbonate precipitation was uneven, resulting in ineffective immobilization of heavy metals in certain areas and causing secondary pollution. Ultimately, the project failed to achieve the expected outcomes, leading to economic losses and environmental issues.

Lessons Learned:

1) Control of Technical Parameters: The successful application of EICP technology requires precise control of reaction conditions such as temperature, pH, and enzyme activity. Strict monitoring and regulation of these parameters during implementation are essential to ensure the uniformity and stability of calcium carbonate precipitation.
2) Preliminary Investigation and Assessment: Prior to undertaking large-scale environmental remediation projects, a comprehensive preliminary investigation and environmental impact assessment must be conducted to understand the distribution and concentration of contaminants and to develop a scientifically sound remediation plan.

3) Continuous Monitoring and Evaluation: Throughout the project implementation, ongoing monitoring and evaluation should be conducted to promptly identify and address issues, ensuring the effectiveness of remediation and environmental safety.

#### 5.2.2. A Building Foundation Treatment Project

In a building foundation treatment project, the construction team’s insufficient understanding and improper operation of EICP technology led to multiple technical errors during the process, such as incorrect ratios of enzyme to calcium source and improper control of injection depth and timing, ultimately failing to produce effective calcium carbonate precipitation. As a result, the load-bearing capacity and stability of the foundation soil did not significantly improve. The project was not completed on schedule, causing severe delays and cost overruns.

Lessons Learned:

1) Technical Training and Guidance: The successful application of EICP technology requires specialized technical knowledge and operational skills. Prior to project implementation, comprehensive training and guidance should be provided to the construction team to ensure they possess the correct technical competencies.
2) Scientific Planning and Management: During project implementation, scientific planning and management should be conducted, with detailed construction plans and operating procedures established to ensure that every stage is executed according to standards, thereby avoiding technical errors and operational deviations.
3) Multi-party Collaboration and Coordination: During the application of the technology, collaboration and coordination with research institutions, technical experts, and relevant stakeholders should be strengthened. Leveraging the expertise and experience of all parties will enhance the success rate and technical quality of project implementation [12].

## 6. FUTURE PROSPECTS

### 6.1. Technological Innovation and Development Directions

#### 6.1.1. Optimization and Improvement of Technology

The future development of EICP technology requires continuous optimization of existing methods to enhance its efficiency and stability. Current research primarily focuses on the following areas:

1) Enhancement of Enzyme Activity: Develop highly efficient and durable urease enzymes to improve enzyme activity and stability, thereby increasing the efficiency of the EICP reaction.
2) Optimization of Reaction Conditions: By controlling reaction parameters such as temperature, pH, and ion concentration, optimize the formation process of calcium carbonate precipitation to ensure its uniformity and stability.
3) Introduction of New Materials: Explore alternative biocatalysts or enzymes, study the effects of different materials on the EICP reaction, and seek more efficient and cost-effective alternatives [13].

#### 6.1.2. Expansion of Application Fields

The future development of EICP technology is not limited to soil improvement and foundation reinforcement but can also be extended to a wider range of application fields:

1) Groundwater Pollution Remediation: Utilize EICP technology to immobilize contaminants underground, reducing their migration and diffusion, thereby protecting groundwater resources.
2) Cultural Heritage Preservation: Repair and reinforce historic buildings and artifacts using EICP

technology to extend their service life and protect cultural heritage.

3) Marine Engineering: In marine engineering, EICP technology can be used to reinforce and protect seabed soils, enhancing the safety and stability of marine structures [14].

### 6.1.3. Digitalization and Intelligentization

With the advancement of digital and intelligent technologies, EICP is also expected to evolve toward more intelligent applications:

1) Intelligent Monitoring and Control: Utilize sensors and Internet of Things (IoT) technologies to monitor and control the EICP reaction process in real time, ensuring the stability and effectiveness of the reaction.
2) Data Analysis and Modeling: Leverage big data and artificial intelligence technologies to analyze and model data from EICP applications, optimize technical solutions, and enhance application efficiency.

## 6.2. Ethical Guidelines and Policy Recommendations

### 6.2.1. Environmental Ethical Guidelines

Environmental Impact Assessment: Prior to the application of EICP technology, a thorough environmental impact assessment must be conducted to evaluate the potential effects on ecosystems and the environment, ensuring the environmental safety of the technology.

Sustainable Development: The application of EICP technology should adhere to the principles of sustainable development, minimizing negative environmental impacts while achieving a balance between economic and environmental benefits [15].

### 6.2.2. Social Ethical Guidelines

Public Participation and Transparency: During the promotion and application of the technology, emphasis should be placed on public engagement to ensure transparency and openness, fully considering the needs and opinions of stakeholders.

Technical Education and Training: Strengthen the technical education and training of relevant personnel to enhance their understanding and operational skills of EICP technology, ensuring its proper application and dissemination.

### 6.2.3. Economic Ethical Guidelines

Equitable Resource Allocation: The distribution of technological resources and funding should emphasize fairness and justice, ensuring that diverse regions and communities can benefit from the development and application of the technology.

Cost-Benefit Analysis: A detailed cost-benefit analysis should be conducted prior to technology application to ensure its economic feasibility and maximize benefits.

### 6.2.4. Policy Recommendations

Technical Standards and Regulations: Develop and improve relevant standards and regulations for EICP technology to ensure the scientific and standardized application of the technology, promoting its standardized development.

Government Support and Incentives: Governments should increase support for the research, development, and application of EICP technology, promoting its dissemination and adoption through policy incentives and financial subsidies.

International Cooperation and Exchange: Strengthen cooperation and communication with the international community, learn from advanced foreign technologies and experiences, and promote innovation and development of EICP technology [16].

## 7. CONCLUSION

This paper provides a detailed discussion on the application of enzyme-induced calcium carbonate precipitation (EICP) technology in soil improvement, revealing its technical principles, application areas, advantages, and limitations, along with ethical considerations and case analyses. The main findings and viewpoints are summarized as follows:

Technical Principles: EICP technology employs urease to catalyze the hydrolysis of urea, producing calcium carbonate precipitation that improves soil structure and enhances soil stability. This biochemical process offers a low-energy, environmentally friendly solution for soil improvement and environmental remediation.

Application Areas: EICP technology shows broad prospects in soil structure improvement, foundation reinforcement, and pollution remediation. Practical cases demonstrate its effectiveness in enhancing soil shear strength and load-bearing capacity, as well as in immobilizing heavy metals and organic contaminants.

Advantages and Limitations: EICP technology offers environmental friendliness, low energy consumption, ease of operation, and wide applicability. However, it also faces technical challenges such as difficulties in reaction control, uncertainties in long-term effects, and cost concerns.

Ethical Considerations: From an environmental ethics perspective, EICP technology requires comprehensive evaluation of its potential environmental impacts and sustainability. Socially, its promotion and application should emphasize public participation and transparency, balancing the interests of various stakeholders. Economically, detailed cost-benefit analyses are necessary to ensure fairness and economic feasibility of the technology’s application.

Case Analysis: Analyses of successful domestic and international cases demonstrate the significant effectiveness and social benefits of EICP technology in practice. Meanwhile, lessons from failure cases highlight the necessity of strict control over reaction conditions, enhanced technical training, and management to ensure successful project implementation.

Future Prospects: The future development of EICP technology requires innovations in technical optimization and improvement, expansion of application fields, and digitalization and intelligentization. Concurrently, the formulation and adherence to relevant ethical guidelines and policy recommendations are essential to promote sustainable development and widespread adoption of the technology.

In summary, this paper offers a comprehensive theoretical analysis and practical guidance for the application of EICP technology in soil improvement, while acknowledging certain limitations. Future research should focus on accumulating experience through broader practical applications, continuously refining and innovating the technology to enhance its effectiveness in soil improvement and environmental remediation, thereby achieving sustainable development and widespread utilization.

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