

Chapter

Research and Application Progress of Biochar in Amelioration of Saline-Alkali Soil

Peng Zhang, Yuning Wang, Fude Liu, Le Jiao and Hongwen Sun

Abstract

Saline-alkali soils pose a significant global challenge to agricultural productivity, necessitating sustainable remediation strategies to unlock their cultivation potential. Biochar has emerged as a promising soil amendment, exhibiting multifunctional capabilities in pH regulation, contaminant immobilization, carbon sequestration, and nutrient retention. However, the heterogeneous nature of biochar compositions results in inconsistent remediation outcomes, while the mechanistic understanding of its interactions with saline-alkali soils remains incomplete. This chapter provides a comprehensive analysis of the effects of biochar on the physicochemical properties, nutrient availability, and biological characteristics of saline-alkali soils. It summarizes the improvement effects of both biochar and modified biochar on saline-alkali soils, evaluates their impacts on quality and efficiency, and elucidates the potential mechanisms underlying biochar's role in saline-alkali soil remediation. Furthermore, this chapter outlines future research directions to provide a reference for developing green, efficient, and precise biochar-based technologies tailored to saline-alkali soil remediation, bridging the gap between fundamental research and large-scale agricultural applications.

Keywords: saline-alkali soil, biochar, modification, physicochemical property, nutrient

1. Introduction

Soil salinization is recognized as one of the most significant challenges threatening agricultural production, food security, and sustainable development in arid and semi-arid regions globally. Currently, the global saline-alkali land area is approximately 1.1×10^9 hm^2 (accounting for 8.7% of the Earth's total land area) [1]. These areas are predominantly located in naturally arid or semi-arid regions of Asia, Africa, and Latin America. Saline-alkali lands are typically characterized by a scarcity of freshwater resources, low terrain, high groundwater levels, and difficulties in soil desalination [2]. The issues of declining soil fertility, poor crop growth, and fragile ecological environments caused by soil salinization severely constrain regional agricultural, forestry, and urban development. Developing soil conditioners that are highly compatible with traditional physical, chemical, and biological

improvement techniques, as well as engineering measures, represents a key strategy for the green, efficient, and precise improvement and comprehensive utilization of saline-alkali land.

In recent years, biochar technology has emerged as a research hotspot in the fields of soil science and environmental science. It is considered an important “multi-functional” technology capable of addressing major challenges affecting human sustainable development, such as climate change [3], agricultural production safety [4], energy crises [5], agricultural waste resource utilization [6], and environmental pollution [7]. This has sparked a global research and development boom. Biochar is a highly aromatic carbonaceous material produced through the pyrolysis and carbonization of animal and plant residues under completely or partially oxygen-deficient conditions. It exhibits characteristics such as a large specific surface area, strong adsorption capacity, and anti-decomposition properties [5], and plays positive roles in soil improvement, crop yield enhancement, and environmental protection. Extensive studies have demonstrated that biochar exerts direct or indirect regulatory effects on soil nutrients [8], increases soil organic matter content, cation exchange capacity (CEC), permeability, and microbial activity [9], reduces nitrogen and phosphorus losses, enhances soil aggregate structure formation [10], and improves soil water conductivity to facilitate water infiltration, thereby optimizing crop habitats and increasing yields. Over the past two decades, biochar technology has achieved notable progress in the improvement and application of saline-alkali land. Numerous studies have confirmed the beneficial effects of biochar application on saline-alkali soil properties, including enhancing soil permeability and organic matter content [9], reducing pH and salinity [11], and promoting microbial and crop growth [12]. However, due to the high salt ion content and strong alkalinity of biochar produced at large scales, some studies have also reported negative impacts, such as increased soil pH and salt content [13]. These findings indicate that current biochar technology exhibits contradictions and lacks systematicness in saline-alkali land improvement, which hinders accurate prediction and evaluation of its scientific and practical value for different types of saline-alkali land in China. Additionally, due to the complex interaction processes between biochar and soil, some research results remain superficial, and the elucidation of microscopic mechanisms requires further refinement. Therefore, as a novel comprehensive remediation technology for saline-alkali land, a comprehensive and systematic evaluation of the application value of biochar technology in saline-alkali land improvement, clarification of relevant processes and micro-mechanisms, and identification of its advantages and disadvantages can provide correct guidance for the widespread application of biochar technology in saline-alkali land improvement in China and promote the healthy development of biochar-based improvement technologies.

Based on this, this chapter systematically reviews the research status of biochar in saline-alkali land improvement over the past 20 years, analyzes and summarizes the influence of biochar on the physical and chemical properties, nutrient availability, and biological characteristics of saline-alkali soils, and elucidates the key mechanisms of biochar improvement and its potential application value in combination with the unique characteristics of biochar. Finally, in light of existing problems and deficiencies, future research directions and prospects are proposed. This study aims to provide a theoretical basis for promoting and applying biochar technology in saline-alkali land improvement and contribute to the exploration and development of green, low-carbon, environmentally friendly, and sustainable saline-alkali land improvement technologies.

2. Effect of biochar on the physicochemical properties of saline-alkali soil

Biochar exhibits a high specific surface area, complex pore structure, and abundant functional groups. These characteristics enable biochar to play multiple roles in the improvement of saline-alkali land [14]. The physicochemical properties of biochar are influenced by various factors, including the type of raw materials, pyrolysis temperature, preparation method, heating rate, and residence time [15]. These factors also significantly affect the promoting effects of biochar on the physicochemical properties of saline-alkali soil, water and salt transport and distribution, as well as agricultural productivity. Based on numerous studies, the addition of biochar prepared from different raw materials and pyrolyzed under varying conditions has diverse impacts on soil properties, such as soluble salt content, pH, bulk density, CEC, organic matter content, and crop growth and yield in different types of saline-alkali soils.

Total soil salinity and degree of alkalization (exchangeable sodium percentage (ESP)) are critical indicators for assessing the extent of soil salinization and alkalization. Saline-alkali soils are typically characterized by high salt content, high electrical conductivity (EC), and elevated ESP due to the accumulation of large amounts of salts. Reducing the soluble salt content and ESP in the soil, alleviating salt stress on soil organisms, and restoring soil ecological functions remain the core objectives of saline-alkali land improvement. In the early stages of biochar technology development, biochar was primarily produced through high-temperature pyrolysis, resulting in materials rich in alkali metal ions and exhibiting strong alkalinity. Consequently, earlier studies predominantly focused on its application in improving acidic soils. However, in recent years, an increasing number of studies [16, 17] have highlighted the potential of biochar in mitigating the adverse effects of saline-alkali soils. These studies confirm that biochar can effectively reduce the salt content and ESP of saline-alkali soils. The mechanisms underlying biochar's ability to reduce soil salinity and ESP in saline-alkali soils can be attributed to two primary aspects: (1) The biochar surface is enriched with exchangeable ions such as Ca^{2+} and Mg^{2+} , which can displace adsorbed Na^+ from soil colloids, thereby reducing sodium salt content in the soil [18]; and (2) Biochar significantly enhances soil porosity and specific surface area, improves soil water retention capacity, and facilitates the leaching of sodium salts from the soil [19, 20].

Biochar can alter the soil pH of saline-alkali land, primarily attributed to the leaching of substances such as alkali metal ions and carbonates that are abundant in biochar. However, these changes are influenced by the type of biochar raw materials and pyrolysis temperature. For example, Sun et al. [21] reported that when wheat straw biochar (pH = 6.9), corn straw biochar (pH = 8.0), and peanut shell biochar (pH = 7.7) were added to coastal sodium chloride saline-alkali soil (pH = 8.6), only wheat straw biochar significantly increased the soil pH, while no significant changes were observed with the other two types. Further studies have confirmed that as pyrolysis temperature increases, the ash content of biochar rises, leading to enhanced alkalinity [22]. Conversely, biochar produced at low pyrolysis temperatures (< 500°C) tends to be neutral or weakly alkaline, making it more suitable for improving saline-alkali soils [18]. Additionally, research has shown that biochar produced via hydrothermal methods exhibits acidity and can effectively reduce soil pH [23]. However, this preparation method imposes high demands on equipment, involves significant technical challenges, and exhibits poor safety performance, thereby limiting its potential for large-scale production. In summary, the effectiveness of biochar in altering the soil pH of saline-alkali land is constrained by multiple factors, including soil type, biochar raw materials, pyrolysis temperature, biochar properties, and application methods.

The porosity of saline-alkali soil is generally low [1], which restricts plant growth. Numerous studies [24, 25] have demonstrated that biochar can significantly enhance the porosity of saline-alkali soil, particularly in the topsoil layer (0–30 cm), with increases ranging from 4.8 to 30.1%. This effect is directly attributed to the high intrinsic porosity of biochar, which, upon incorporation into the soil, directly elevates the overall soil porosity [26]. Additionally, the poor physical conditions of saline-alkali soil, such as low porosity and high bulk density, are mitigated by biochar's large specific surface area, low density, stable porous structure, and significantly lower bulk density compared to saline-alkali soil [27]. Biochar not only improves soil aggregate structure and enhances aggregate stability but also increases soil porosity while containing substantial organic matter that dilutes soil mineral components [24], indirectly reducing soil bulk density. Therefore, for improving the porosity and bulk density of saline-alkali soil, biochar with low bulk density, high porosity, and low ash content should be prioritized, such as straw-derived biochar produced at high pyrolysis temperatures (> 600°C) [28, 29].

Saline-alkali soils exhibit low organic matter content, and their exchange sites are predominantly occupied by salt ions such as Na^+ , limiting the soil's capacity to retain other cations and resulting in a low CEC. Consequently, CEC serves as a critical indicator for evaluating the improvement of saline-alkali soils. Extensive research has confirmed that biochar, due to its abundance of functional groups (e.g., -OH and -COOH), enhances its adsorption capacity for soil cations, effectively increasing the CEC of saline-alkali soils by 22.5–82.0% [30, 31]. The mechanisms underlying this enhancement include: (1) Biochar's high specific surface area and rich oxygen-containing functional groups (e.g., carboxyl and hydroxyl groups) and metal minerals directly increase soil exchange sites [18]; and (2) The pH increase induced by biochar leads to soil colloid deprotonation, promoting an increase in soil CEC [32]. The determination of biochar's CEC value hinges on its surface oxygen-containing functional groups and metal mineral composition, leading to variations in CEC values among biochars prepared from different raw materials at varying temperatures [33]. Currently, limited research exists on the mechanisms of biochar's effects on saline-alkali soil CEC, particularly regarding the interplay between environmental factors (e.g., flooding and drought), soil texture, biochar properties, and saline-alkali soil improvement, necessitating further long-term field experiments for clarification. Soil carbon constitutes the largest terrestrial carbon pool, and even minor changes in soil carbon can significantly impact atmospheric CO_2 concentrations and the global carbon cycle. As a soil amendment rich in organic carbon, biochar has been shown in numerous studies to enhance carbon sequestration in saline-alkali soils [34] and reduce greenhouse gas emissions [35]. Upon entering the soil, biochar exhibits two primary mechanisms: carbon sequestration (increasing carbon sinks) and enhanced carbon emissions. These mechanisms influence the exchange of three major greenhouse gases (CO_2 , CH_4 , and N_2O) [36] between farmland systems and the atmosphere. Whether biochar acts as a net carbon sink depends on the dominance of these mechanisms. Key carbon sequestration mechanisms include: (1) Biochar's high proportion of recalcitrant carbon enables long-term sequestration within the soil, forming a stable carbon reservoir [37]; (2) Its large specific surface area facilitates the adsorption of organic and inorganic substances containing C and N, generating more stable organic–inorganic complexes and reducing carbon decomposition and release [38]; and (3) By regulating soil properties, inhibiting microbial activity, and reducing enzyme activity, biochar influences soil carbon and nitrogen cycles, thereby modulating soil respiration, nitrification, and denitrification reactions to mitigate

greenhouse gas emissions [39]. Overall, biochar represents an effective amendment for enhancing soil organic carbon and carbon sink levels in saline-alkali land. Future research should focus on elucidating the regulatory mechanisms of biochar on soil carbon sequestration and carbon emissions in saline-alkali land, further exploring biochar's potential for soil carbon storage, and providing theoretical and technical support for precise regulation of soil carbon cycles in saline-alkali land.

3. Effects of biochar on nutrient availability in saline-alkali soil

Due to the poor soil structure in saline-alkali soils, anions such as Cl^- , SO_4^{2-} , and OH^- compete with nutrients like N and P for adsorption sites on soil particles [40], leading to the easy loss of soil nutrients through water flow or leaching. Additionally, the scarcity of available nutrients in saline-alkali soils results in extremely low nutrient utilization rates by plants [41]. Biochar is inherently rich in essential nutrients such as N, P, K, and minerals, and can significantly enhance the nutrient content in saline-alkali soils. The primary mechanisms are as follows: (1) Directly increasing soil nutrient levels through its inherent nutrient content [42]. For instance, biochar derived from livestock and poultry manure exhibits relatively high nitrogen content [43]. Moreover, the water-soluble nitrogen and phosphorus content in biochar gradually decreases with increasing pyrolysis temperature [44–46]. And as pyrolysis temperature increases, inorganic orthophosphate (PO_4^{3-}) becomes the sole form of phosphorus in manure-derived biochar at 500°C, while water-soluble phosphorus is nearly absent at high temperatures ($\geq 700^\circ\text{C}$). Therefore, low-temperature biochar derived from livestock and poultry manure is a more suitable choice for enhancing nutrient content in saline-alkali soils. (2) Biochar enhances soil aggregate stability [47], thereby improving the soil's capacity to retain nutrients and reducing nutrient leaching [8]. (3) Biochar alleviates salt stress in crops and promotes the absorption of free nutrients in the soil, which benefits crop growth [48].

Simultaneously, biochar influences the cycling of nitrogen (N), phosphorus (P), and potassium (K) (NPK) elements in the soil by enhancing microbial activity and soil enzyme activity, thereby reducing nutrient losses [41]. For example, biochar reduces ammonia (NH_3) and nitrous oxide (N_2O) emissions [49], minimizes NO_3^- leaching [47], promotes nitrification, and enhances nitrogen fixation [50], thus increasing the proportion of plant-available N in the soil. Biochar also increases phosphatase activity [9] and the abundance and activity of rhizosphere microorganisms [51], promoting the mineralization of organic phosphorus and converting it into plant-available forms, further enhancing phosphorus availability. The behavior of K in soil differs from those of N and P, as K dynamics are not influenced by microbial activity but are primarily governed by the cation exchange characteristics of the soil [52]. Currently, there is limited research on the mechanisms by which biochar affects potassium in saline-alkali soils; however, some studies indicate that biochar application significantly increases soil CEC and available potassium content [53].

4. Effects of biochar on soil biological properties in saline-alkali soil

The capacity of saline-alkali land to support plants, animals, microbial abundance, and enzyme activity is significantly lower than that of normal soil [54]. Numerous studies have investigated the effects of biochar addition on the structure and abundance

of soil microbial communities in saline-alkali land. Research has demonstrated that due to its high specific surface area, porous structure, and rich content of organic matter, N, P, K, and other nutrients, biochar can increase the levels of soluble organic matter and inorganic nutrients in soil, reduce salt content, alleviate salt stress, and thereby enhance microbial abundance and enzyme activity [55, 56]. However, variations in raw materials and preparation processes result in significant differences in the pH and nutrient content of biochar. Tang et al. [22] found that high-temperature biochar (> 550°C) contains fewer toxic functional groups, such as carboxylic acids, phenols, and amines, which promote the transformation of soil microbial communities toward beneficial bacterial groups, such as Proteobacteria and Bacteroidetes. Additionally, the type and application rate of biochar can alter the activity of soil enzymes, such as sucrase, urease, and phosphatase. The application rate of biochar also affects soil enzyme activity; when the application rate is less than 2%, soil enzyme activity increases rapidly, whereas at rates greater than 2%, the increase becomes slower [57].

The community structure and abundance of soil fauna are closely linked to the physicochemical properties of saline-alkali soil. For example, Zhang Jianying et al. [58] reported that the distribution of groups, such as Formicidae, Muridae, and Curculionidae, is negatively correlated with soil pH, alkalinity, and salt content. Soil factors such as total salt and total nitrogen play a decisive role in shaping the composition of soil animal communities in saline-alkali land. By reducing soil salt content and improving soil physicochemical properties, biochar provides a more suitable habitat for soil fauna. In contrast to the extensive research on soil microorganisms and enzymes, there are relatively few studies on the interactions between biochar and small-to-medium-sized soil fauna such as earthworms in saline-alkali land. Some studies have focused on the inherent ecological risks of biochar, such as polycyclic aromatic hydrocarbons (PAHs) and persistent free radicals, which may be toxic to soil fauna and inhibit their growth and reproduction [29]. These negative effects of biochar on soil fauna indirectly highlight the ecological risks associated with biochar use in saline-alkali land remediation. Therefore, ensuring the ecological safety of biochar is an urgent issue that must be addressed in future saline-alkali land management strategies.

For terrestrial plants, growing in saline-alkali land presents significant challenges. First, high salt stress in soil solution directly inhibits plant growth. Second, poor soil structure and severe deficiencies in air and water lead to underdeveloped root systems and low emergence rates. Finally, nutrient scarcity results in poor plant nutrition. As discussed earlier, biochar performs effectively in addressing high salt content, poor soil structure, and low nutrient availability, providing a favorable growth environment for plants. However, persistent free radicals in biochar [59] can accelerate plant cell aging, disrupt the growth and metabolic cycles of epidermal cells, and inhibit plant development. Furthermore, high application rates of biochar [60] and increased soil pH and salt content following biochar application may negatively affect plant growth and development. Therefore, future research should focus on elucidating the intrinsic effects and mechanisms of biochar on crops and prioritize the development of novel biochar types with low salt, low toxicity, and high efficiency for saline-alkali land improvement.

5. Amelioration effect of modified biochar for saline-alkaline soil

Although biochar offers numerous advantages for the amelioration of saline-alkaline soil, its single application not only requires large quantities and incurs high

costs but may also increase the soil pH and salt content, negatively impacting saline-alkaline soil. To address these issues, various biochar modification techniques have been proposed to enhance quality and efficiency, including acid washing and activation, loading active components, and physical mixing with traditional fertilizers or soil amendments [61, 62]. Modified biochar exhibits advantages that primary biochar cannot match, significantly enhancing its amelioration effects on saline-alkaline soil [63, 64].

To overcome the strong alkalinity of conventional pyrolyzed biochar, researchers have developed methods involving treatment with strong acids such as nitric acid and hydrochloric acid, known as acid-modified biochar [65, 66]. After acid treatment, inorganic components and organic matter leach from the surface and pores of biochar, while alkaline components are removed or neutralized. This process exposes more micropores, increases the specific surface area [67], and enhances oxygen-containing functional groups [68], thereby strengthening biochar's adsorption capacity for soil salt ions. Additionally, acid-modified biochar significantly improves soil porosity and permeability, increasing the proportion of water-stable large aggregates [28]. Some studies have also demonstrated that preparing biochar via hydrothermal treatment in a strong acid environment [65] can retain more acidic oxygen-containing functional groups and pore structures [69], enhancing its adsorption capacity for soil salt ions [70] and improving its amelioration effects on saline-alkaline soil. Despite extensive research on strong acid modification, challenges remain regarding stability, economic cost, and amelioration efficiency in practical saline-alkaline soil applications, necessitating further evaluation in future studies.

Due to the limited nutrient content in biochar, its single application cannot provide sufficient nutrients for crops [71]. Consequently, researchers have developed biochar-based fertilizers, which can directly supplement required nutrients [72], delay nutrient release in the soil, reduce nutrient loss, and serve as carriers for enhancing fertilizer efficiency [73]. However, the effects and mechanisms of different fertilizer types vary: (1) Organic fertilizers such as poultry manure are rich in organic carbon, increasing the abundance of soil microbial communities in saline-alkaline soil and promoting crop growth [74]. Simultaneously, the clogging of micropores by adsorbed compost-derived substances reduces biochar's surface area, alleviating the negative effects of excessive biochar on soil [75]. (2) Combining biochar with inorganic fertilizers such as nitrogen and phosphorus fertilizers generates higher levels of available nutrients, enhancing soil enzyme activity and microbial abundance in saline-alkaline soil [76]. Moreover, biochar adsorbs nutrients, reducing the leaching of inorganic nitrogen and phosphorus in the soil. Notably, due to the adsorption or precipitation reactions of orthophosphate (PO_4^{3-}) at higher pH values, phosphorus fertilizers and biochar in saline-alkaline soil may exhibit negative interactions [77]. (3) When co-applied with microbial fertilizers, biochar not only provides nutrients to plants as a fertilizer but also creates suitable habitats for microorganisms [78], mitigating the stress caused by harsh saline-alkaline soil conditions [79]. Overall, the application of biochar-based fertilizers significantly enhances biochar's amelioration efficiency on saline-alkaline soil while reducing economic costs. However, further research is needed to evaluate the applicability of biochar-based fertilizers for different types and textures of saline-alkaline soils, providing critical guidance for precise fertilization control and improving biochar utilization efficiency.

The development of new composite materials (amendments) through physical and chemical combinations of biochar and loadings represents a current research hotspot. Due to its rough and porous surface morphology, biochar serves as an excellent carrier

medium. Loading substances generate new functional groups and salt ion adsorption sites on biochar's surface. Common loading substances include metal compounds and clay minerals. The mechanisms by which biochar-based composite materials improve saline-alkaline land primarily include those given as follows: (1) Loading substances introduce new elements and functional groups [80], enhancing biochar's complexation and precipitation capacities for soil soluble salt ions, reducing soil soluble salt content and alkalinity. Zhang et al. [81] noted that after biochar was loaded with red phosphorus, new phosphorus-containing functional groups formed on its surface, creating new phosphorus-containing minerals with soil metal ions. This significantly reduced the electrical conductivity and soluble salt content of saline-alkaline soil while increasing plant-available phosphorus content. (2) New substance loading provides additional adsorption sites for soil nutrients such as nitrogen and phosphorus, reducing nutrient leaching [82]. (3) Metal species such as iron, calcium, and magnesium loaded in composite materials release large numbers of metal cations, exchanging adsorbed Na^+ in soil colloids, accelerating Na^+ migration during soil percolation, improving soil leaching effects, and reducing sodium salt content [83]. In summary, biochar-based composite materials integrate the advantages of biochar and loading substances, enabling efficient and precise improvement and governance of saline-alkaline land by tailoring loads to regional saline-alkaline soil types.

6. Conclusions and prospects

Biochar technology has emerged as a research hotspot in soil science and environmental science in recent years, achieving notable progress in the improvement of saline-alkali land. Specifically, biochar exhibits a large specific surface area and strong adsorption capacity, enabling it to directly or indirectly regulate soil nutrients. It enhances soil organic matter content, CEC, permeability, and microbial activity in saline-alkali land, reduces nitrogen and phosphorus losses, and promotes the formation of soil aggregate structures. Biochar plays a positive role in soil improvement, water retention, and crop resistance to salt and alkali stresses in saline-alkali land. Additionally, when biochar is returned to agricultural fields, it expands the soil carbon pool and demonstrates superior carbon sequestration and emission reduction effects compared to other agricultural practices. Biochar-based fertilizers or composite materials used for saline-alkali land improvement can delay fertilizer release, enhance soil fertility persistence, and improve crop adaptability to saline-alkali conditions. However, numerous challenges remain in the research and application of biochar for saline-alkali land improvement, necessitating further investigation:

1. Basic theoretical research on biochar improvement of saline-alkali land remains controversial and uncertain. The impacts of biochar on the physicochemical properties and functions of saline-alkali soils, the geochemical cycles of key elements such as nitrogen and phosphorus, the succession and functions of soil microbial communities, and the underlying regulatory mechanisms are not fully understood. In particular, the correlation between biochar properties and the improvement effects on different types of saline-alkali land requires further systematic research and validation.
2. Most studies on biochar improvement of saline-alkali land are still at the laboratory simulation stage, with a lack of long-term, fixed-point, and large-scale field

experiments to analyze its practical applicability and mechanisms of action. For example, whether the patterns of soil water and salt movement under biochar influence are affected by saline-alkali land type, agronomic measures, and irrigation conditions remains unclear. Additionally, the effects of microorganisms and crop roots on the structure and stability of biochar-soil aggregates require further exploration. Simultaneously, factors, such as biochar aging, climate, geology, and hydrology, should be comprehensively considered. Long-term dynamic tracking and monitoring of biochar, combined with soil quality evaluations, are essential to assess the sustainability of biochar's improvement effects and associated environmental risks.

3. Batch production and large-scale application of modified biochar face significant obstacles. Research on raw material selection and preparation processes is predominantly at the laboratory stage, making it challenging to achieve efficient and cost-effective large-scale production. Moreover, the actual soil environment of saline-alkali land is a complex and diversified system, and the performance of modified biochar in real-world soils is influenced by various conditions. Future research should focus on advancing biochar modification methods and principles, promoting large-scale applications, conducting economic cost assessments, and enhancing environmental safety.

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