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A Meta-Analysis on the Effects of Modified Biochar Preparation and Structural Regulation on the Remediation of Soils Contaminated by Heavy Metals and Other Pollutants

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ABSTRACT

To investigate the effects of biochar preparation and structural regulation on the remediation of heavy-metal-contaminated soils in China, this study used a Meta-analysis method to systematically collect and integrate published literature worldwide including field experiments, pot experiments, and laboratory incubation studies. We quantitatively evaluated the influences of straw-derived biochar properties such as feedstock type, pyrolysis temperature, modification method, and application rate on soil physicochemical properties and the remediation efficiency for soils contaminated with lead (Pb), cadmium (Cd), and arsenic (As). The results showed that modified biochar significantly improved soil physicochemical properties. Compared with the control group, the average increases in soil pH, soil organic carbon (SOC) content, and cation exchange capacity (CEC) reached 10.34%, 36.48%, and 23.42%, respectively. Among different modification methods, thiourea modification had the most obvious effect on increasing soil pH (25.83%), microbial modification most prominently promoted SOC (61.25%), and Mn modification increased CEC by up to 132.69%.In terms of biochar intrinsic properties, biochar with pH 9–10 achieved the highest SOC improvement (46.38%); pyrolysis temperature above 700°C performed best in enhancing pH and CEC (21.08% and 74.56%, respectively); application rate of 1%–2% led to the largest CEC increase (55.72%), while 2%–5% most effectively improved SOC (35.18%). For soil conditions, modified biochar increased CEC most significantly in alkaline soils (48.08%), and the improvement in sandy soils was markedly higher than in other soil textures. For heavy metal remediation, the immobilization of Pb by modified biochar was dominated by pH and ash content, with the best performance at high temperature (>700°C) and application rate of 4%–6%. The optimal conditions for Cd remediation were lignocellulosic feedstock, organic modification, and 2%–3% application rate, which reduced soil available Cd and plant Cd content by 65.01% and 70.72%, respectively. For As remediation, high-temperature pyrolysis (>450°C) combined with Fe/Mn modification and an application rate of 0.5%–2% showed the most significant effects. Split application maintained soil pH more effectively than a single basal application.

KEYWORDS

Biochar, Heavy Metals, Modification, Adsorption, Soil Remediation.

1. INTRODUCTION

1.1. Overview of Soil Contamination by Heavy Metals and Other Pollutants

1.1.1. Hazards of Heavy Metal and Other Contaminants in Soil

Globally, soil contamination by heavy metals is becoming increasingly severe. Residual heavy metals in soil not only disrupt ecosystem stability and balance but also accumulate progressively through the food chain. This accumulation poses long-term and serious risks to plant and animal growth as well as human health, leading to a series of unpredictable environmental hazards. Therefore, remediating heavy metal-contaminated soil and improving soil environmental quality have become urgent tasks[1].

In recent years, against the backdrop of rapid industrialization and urbanization, excessive levels of heavy metals such as cadmium (Cd), lead (Pb), and arsenic (As) in farmland soils have become increasingly prominent in some regions of China. This issue has emerged as a major constraint on green and sustainable agricultural development and on ensuring the safety and quality of agricultural products. Heavy metal contamination in farmland soils is characterized by high concealment, significant accumulation effects, and difficulty in reversal. It not only directly degrades soil ecological functions but also poses potential and persistent threats to human health through food chain enrichment and transfer[2].

Heavy metal contamination originates from both anthropogenic activities and natural processes. Among these, human factors such as mining, metal smelting, industrial wastewater discharge, and agricultural practices are the main drivers of pollution. Lead, cadmium, and arsenic are typical heavy metal elements with high toxicity and strong mobility. They are released in large quantities during industrial and agricultural activities and continuously infiltrate the soil, posing a long-term contamination risk.

Among various pollutants affecting the environmental quality of agricultural soils, heavy metals play a dominant role, and cadmium (Cd) is the most prominent primary contaminant[3]. Cadmium is a highly toxic heavy metal and has been listed as a priority pollutant by the United Nations Environment Programme. It significantly inhibits plant growth and development, leading to reduced photosynthesis, poor root development, yield loss, and even plant death in severe cases. After being taken up and accumulated by crops, cadmium enters the food chain. Long-term intake can cause irreversible damage to the human kidneys, bones, and nervous system[4].

Lead (Pb(II)) can damage the nervous and reproductive systems in the human body. Long-term exposure to high-lead environments may lead to conditions such as atrophic gastritis and Alzheimer's disease, and can even cause death in severe cases[5].

Arsenic (As) inhibits cellular respiratory enzymes and damages the central nervous system, with a long latency period. As a strong carcinogen, it can easily cause various cancers and also significantly affect ecosystems[6].

1.1.2. Current Status of Heavy Metal and Other Contamination in Soils of China

A national survey by the Ministry of Environmental Protection of China indicates that soil contamination in some regions of the country is severe. This poses a major threat to ecosystems, food safety, and agricultural development. Currently, over 10 million hectares of farmland are contaminated, accounting for more than 10% of the total arable land area. Among this, heavy metal contamination (mainly Cd, Pb, and As) affects about one-fifth of the contaminated farmland. Each year, more than 10 million tonnes of grain are contaminated by heavy metals, causing economic losses of up to tens of billions of yuan[7].

Cadmium (Cd) mainly comes from mining, metallurgy, electronics, and cadmium-containing fertilizers. It is easily accumulated and difficult to remediate. Cd can spread through multiple media and enter the food chain, endangering human health and agricultural production. Arsenic (As) originates from industrial emissions and arsenic-containing pesticides and fertilizers. It often exceeds safety limits in groundwater, posing serious risks to ecosystems and human health. Both contaminants urgently require remediation.

Most environmental lead (Pb) eventually accumulates in the surface soil and does not easily migrate downward. It tends to bind with organic matter to form insoluble compounds. Excessive Pb can also inhibit crop growth and photosynthesis, reducing both yield and quality[8].

Heavy metals in farmland soils can accumulate in crops through bioaccumulation and undergo transformation. This not only directly affects the quality of agricultural products and exacerbates grain contamination but also further transmits through the food chain, posing potential threats to human health. Therefore, adopting scientific and effective remediation measures is critically important for ensuring the safety and quality of agricultural products, protecting public health, and reducing economic losses.

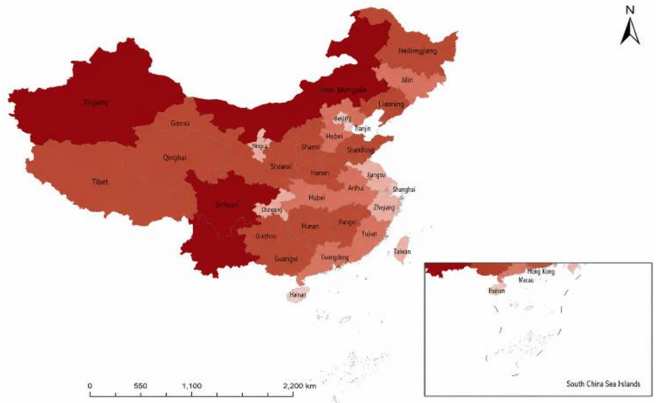

Figure 1 Spatial Distribution Map of Heavy Metal-Contaminated Soils in China

1.1.3. Current Methods for Remediating Heavy Metal and Other Contaminants in Soil

Simply removing heavy metals may lead to their re-activation over the long term. Bioremediation is environmentally friendly and low in cost. To date, extensive research has been conducted worldwide on heavy metal-contaminated soils, and various remediation technologies have been developed. These mainly include physical remediation, chemical passivation, bioremediation, as well as combined technologies such as physical-chemical, chemical-biological, and ecological remediation[9].

The core strategy has shifted from "heavy metal removal" to "risk control and safe utilization". This is achieved by altering the species of the three heavy metals (Pb, Cd, As) and reducing their bioavailability, thereby enabling safe use of contaminated soils.

In soil, each of these three heavy metals exists in five fractions, including exchangeable and carbonate-bound forms, with bioavailability decreasing successively along the fraction sequence. The goal of remediation is to promote their transformation toward less labile, low-activity forms.

Physical remediation can thoroughly and rapidly treat soils highly contaminated with lead, cadmium, and arsenic. However, it requires large engineering efforts, incurs high costs, and may damage soil structure. Therefore, it is only suitable for small, heavily polluted sites and emergency response.

Chemical remediation is highly efficient and widely applicable. It can target specific heavy metals using customized agents, can be scaled up, and costs less than physical remediation. Nevertheless, chemical agents may alter soil physicochemical properties, and the washing wastewater poses a risk of secondary pollution.

Stabilization/solidification techniques cannot completely remove heavy metals and may lead to long-term re-activation. Bioremediation is environmentally friendly and low in cost, preserving soil ecological functions. It is suitable for large areas with low to moderate contamination. However, bioremediation has a long treatment period and limited effectiveness against high-concentration pollution. Hyperaccumulator plants are difficult to screen, and microbial activity is easily affected by soil environmental conditions.

Combined remediation integrates the advantages of multiple technologies. It can synergistically address co-contamination by the three heavy metals, shorten remediation time, and reduce the side effects of any single technology. However, the combination of technologies is complex and requires parameter optimization. The stability and long-term effectiveness of large-scale applications still need validation. This approach is suitable for sites with moderate to severe co-contamination and areas requiring high remediation efficiency and safety[10].

1.2. Application of Modified Biochar in Remediation of Heavy Metal and Other Contaminants in Soil

1.2.1. Concept and Structural Properties of Biochar

The term “biochar” originates from English. In early studies, it was sometimes used interchangeably with “charcoal”. In 2013, the International Biochar Initiative (IBI) defined biochar as a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment.

In line with research on utilizing agricultural and forestry waste, biochar is now widely considered a stable, carbon-rich product formed by pyrolyzing waste biomass (e.g., from farming and forestry) under oxygen-limited or oxygen-free conditions, typically below 700°C. This material consists mainly of aromatic hydrocarbons and graphite-like carbon, with a carbon content exceeding 60%. It also possesses abundant pore structures and a large specific surface area. Therefore, biochar is a functional material for soil improvement, carbon sequestration, and sustainable agricultural development[11].

Biochar is a typical high-carbon material. Its organic carbon content ranges from 70% to 80%. The carbon exists as highly distorted aromatic rings and irregularly stacked layers, which make biochar resistant to decomposition in natural environments and highly stable.

Its outstanding advantages include a large specific surface area and well-developed micropores. In addition, both acidic and basic functional groups are distributed on its surface. Biochar also carries abundant negative charges with high charge density. These features give biochar excellent adsorption capacity.

Notably, using different types of biomass feedstocks or adjusting the pyrolysis temperature can significantly alter the structural characteristics and application performance of biochar.

1.2.2. Concept and Application of Modified Biochar

The application of biochar in remediating heavy metal-contaminated soil is recognized as an efficient ecological remediation approach due to its economic and environmental benefits and ease of operation. In the environmental field, biochar is an important material for addressing climate change and pollution control.

Faced with the dual challenges of global warming and waste of biomass resources, biochar is produced by pyrolyzing biomass and then returned to the soil. This process enables long-term carbon sequestration, creating a “carbon-negative” pathway, while also reducing greenhouse gas emissions such as N_2O and CH_4 from farmland. With its well-developed porous structure and strong adsorption capacity, biochar can be processed into activated biochar to efficiently treat industrial wastewater, purify drinking water, and adsorb pollutants such as SO_2 and NO_x from flue gas. Thus, it plays a key role in carbon sequestration, emission reduction, water purification, and waste gas treatment, contributing to sustainable ecological development[12].

Biochar is also widely used in agriculture. It can be directly applied to soil or made into composite materials to improve soil quality, enhance fertility, and increase crop yield and quality. It is suitable for various scenarios including farmland and forests. Relevant field trials and product development have made some progress worldwide. However, several issues remain in its application. For example, biochar production consumes organic matter that soils may need, and it does not necessarily improve soil fertility. It may also promote microbial decomposition of organic matter, exacerbating soil carbon loss. Some biochars can be degraded by microorganisms, and surface application or deep burial may even intensify the greenhouse effect. Therefore, the view that biochar serves as a permanent carbon sink requires further validation[13].

1.2.3. Immobilization of Heavy Metals and Other Contaminants in Soil by Biochar

Numerous studies have shown that biochar, owing to its unique pore structure and physicochemical properties, has broad application prospects for remediating cadmium-contaminated soil. It can effectively immobilize available Cd in soil and regulate the speciation and distribution of labile Cd, thereby reducing Cd bioavailability[14].

Li Jianrui et al. [15] found that biochar can effectively immobilize Cd, As, and Pb in soil. It reduces the acid-extractable and water-soluble fractions of these metals, decreasing their uptake and accumulation by crops and lowering their mobility and toxicity risks.

Xu Chao et al. [16] conducted a flooding incubation experiment to investigate the effect of biochar on the bioavailability of Cd and Pb in heavy metal-contaminated soil. The results showed that exchangeable Cd and Pb in biochar-amended soil decreased by 1.22%–16.09% and 0.47%–21.51%, respectively, compared to the control group. Moreover, the reduction in exchangeable content for both metals gradually increased with higher biochar application rates.

Additionally, biochar carries abundant negative charges on its surface, which can stably retain heavy metal ions through electrostatic adsorption. The base cations on its surface can also undergo displacement reactions with cadmium ions, thereby effectively immobilizing Cd in soil. Meanwhile, surface functional groups provide binding sites for the formation of heavy metal complexes[17].

Li Li et al. [18] found that corn straw biochar is rich in oxygen-containing functional groups such as carboxyl and phenolic hydroxyl groups, as well as π-conjugated aromatic structures. Through electrostatic interaction-mediated ion exchange and cation-π interactions, these groups convert highly toxic and mobile Cd(II) into stable, adsorbed species, significantly reducing its mobility and bioavailability. Moreover, biochar produced at a high temperature (BC700) adsorbed Cd(II) more firmly, with a desorption rate of only 0.5%.

1.2.4. Effect of Biochar on Plant Uptake of Heavy Metals and Other Contaminants

Heavy metal contamination in soil can significantly harm plant growth and development. It causes damage to cell structure and increases cell membrane permeability[19]. In ecosystems, such heavy metal stress not only leads to natural ecological degradation and reduced crop yields in farmland, but also endangers human health through the food chain. Therefore, remediating soils co-contaminated with cadmium, arsenic, and lead is critically important. Such remediation can alleviate heavy metal stress on plants, restore ecological balance, and help ensure food safety and protect human health.

As an environmentally friendly material, biochar affects crop yield through multiple factors, including crop species, soil properties, biochar characteristics, and climatic conditions. Biochar is rich in various nutrients. It can enhance soil fertility and increase crop yield. Moreover, through electrostatic adsorption, biochar retains nutrients and releases them slowly. This effectively improves soil environment and pH conditions, reduces the levels of available cadmium, arsenic, and lead in soil, and creates favorable conditions for crop growth. Therefore, biochar is a widely applicable and highly effective remediation technique for improving crop growing environments and increasing yield.

Feelet et al. [20] reported that biochar produced from a mixture of manure and fir cones exhibited better cadmium immobilization in soil than biochar derived from a single feedstock. This suggests that mixed-feedstock biochar has potential advantages for heavy metal fixation.

1.2.5. Research Status of Modified Biochar for Remediation of Heavy Metal and Other Contaminants in Soil

Although biochar has some potential for adsorbing heavy metals, its adsorption capacity is relatively limited. To further enhance its adsorption performance, researchers have adopted various modification methods. These mainly include treatment with acids, bases, and oxidizing agents; loading with organic substances; and composite modification with materials containing silicon, iron, aluminum, magnesium, phosphorus, and other components.

Existing studies have shown that after nitric acid modification, biochar not only significantly increases its cation exchange capacity, but also enlarges its specific surface area and pore volume, while introducing abundant oxygen- and nitrogen-containing functional groups. Treatment with strong bases such as KOH and NaOH can also significantly increase specific surface area, pore volume, and the number of functional groups, thereby enhancing the adsorption and stabilization of heavy metals in soil[21].

Wibowo et al. [22] modified biochar with nitric acid. Their results showed that the modified biochar surface carried a large number of acidic oxygen-containing functional groups, and its specific surface area was also significantly increased. Sheng et al. [23] reported that when the mass ratio of KOH to biochar was 3:1, the resulting modified biochar exhibited the best physicochemical properties. These studies all indicate that modification methods can effectively improve the adsorption performance of biochar for heavy metals and other contaminants.

Zhu Sihang et al. [24] prepared biochar from wheat straw, activated it with KOH, and then loaded it with nano-goethite via coprecipitation. This modification successfully introduced a large number of functional groups such as hydroxyl (-OH) and iron-oxygen (Fe-O) bonds onto the biochar surface. The modified biochar (Goethite@BC) showed significantly enhanced complexation and ion exchange capacities, as well as increased specific surface area. Its maximum adsorption capacity for As(III) reached 65.20 mg/g, which is 62.10 times that of unmodified biochar.

Existing studies have confirmed that modified biochars produced by different methods differ significantly from unmodified pristine biochars in their ability to immobilize heavy metals (cadmium, arsenic, and lead).

In practical agricultural settings, multiple factors influence the final remediation outcome of heavy metal-contaminated soils. These factors include the type of biochar feedstock, preparation conditions, modification method, and field application rate.

Meanwhile, related studies have shown that applying biochar to soil for heavy metal remediation significantly increases the abundance and activity of soil microorganisms. Their community structure and composition also change accordingly.

Another study found that bacterial biomass in soil macroaggregates is significantly lower than fungal biomass.

Although current research on modified biochar for immobilizing soil cadmium, arsenic, and lead and for reducing crop uptake of these heavy metals is relatively abundant, systematic comparisons of the effects of different modified biochars under various soil conditions and experimental settings are still lacking.

Biochar feedstocks are diverse, leading to significant variations in physicochemical properties. Modification methods are also numerous and complex. Furthermore, soil conditions, application rates of modified biochar, and crop types differ across studies. These differences result in poor comparability and insufficient reliability of existing experimental results.

Therefore, a comprehensive and systematic quantitative analysis is needed. This analysis should assess how factors such as biochar properties, soil type, and crop species influence the remediation efficacy of modified biochar. Such work is critically important for guiding the application of modified biochar in the practical remediation of heavy metal-contaminated soils.

1.3. Application of Meta-Analysis in the Ecological and Environmental Sciences

1.3.1. Concept of Meta-Analysis

Meta-analysis is a methodological tool that systematically integrates and quantitatively synthesizes results from multiple homogeneous studies. Its core principle is to combine independent experimental data using statistical methods. By increasing the sample size, it enhances statistical power. This approach effectively addresses the limitations of small sample sizes and high heterogeneity in individual studies. Meta-analysis is particularly useful for synthesizing controversial findings, improving the precision of effect estimates, and deriving more generalizable conclusions.

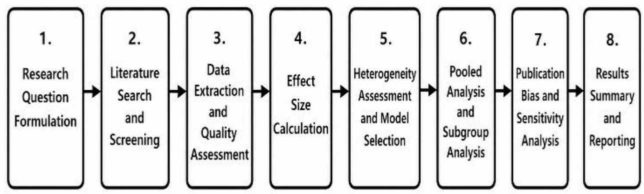

Figure 2 Flowchart of the Meta-Analysis

1.3.2. Significance of Meta-Analysis

Meta-analysis effectively overcomes the strong subjectivity of traditional narrative reviews. It reduces evaluation bias caused by selective inclusion of studies. Through systematic grouping and weighted synthesis, it reveals overall patterns. At the same time, it controls study bias by establishing explicit literature inclusion criteria, ensuring objective and reliable results. Based on integrating homogeneous studies and analyzing sources of heterogeneity, meta-analysis draws robust conclusions and can even uncover new research perspectives. Therefore, as a scientific quantitative synthesis method, meta-analysis has been widely applied in related research.

1.3.3. Application of Meta-Analysis in Evaluating the Effects of Biochar on Agriculture and the Environment

Meta-analysis has become an important quantitative research tool in the ecological and environmental sciences. By systematically integrating results from multiple independent studies, it can draw more comprehensive and reliable conclusions.

To date, many researchers have used meta-analysis to investigate the environmental and agricultural effects of biochar in soil-plant systems. Jeffery et al. integrated 23 studies and found that biochar increased crop yield by approximately 10% on average, with a more pronounced effect for modified biochar in acidic, non-clay soils. Subsequent large-sample meta-analyses yielded similar results, confirming an overall yield increase of about 11% and further highlighting the advantages of biochar application in acidic sandy soils. Biederman et al. showed that biochar significantly increases aboveground plant biomass and crop yield, and improves several soil properties, but has no significant effect on belowground biomass or soil inorganic nitrogen content.

In summary, meta-analysis has unique advantages for objectively evaluating the effects of biochar on agricultural yield improvement and environmental benefits. Therefore, following the meta-analysis approach, this study systematically reviews relevant research on the application of modified biochar for remediating heavy metal-contaminated soils. We comprehensively analyze how factors such as biochar feedstock, modification method, preparation conditions, and soil pH, texture, and type influence heavy metal bioavailability and crop uptake and accumulation. We further elucidate the mechanisms by which modified biochar regulates heavy metal transport and transformation, as well as the changes in microbial communities during remediation. Based on this, we comprehensively evaluate the effectiveness of modified biochar in treating heavy metal-contaminated soils. This work aims to provide a scientific basis for efficiently remediating heavy metal-polluted soils, improving the soil ecological environment, and ensuring the safety of agricultural products and human health.

1.4. Research Objectives, Content, and Technical Approach

1.4.1. Research Objectives and Significance

This study employs a meta-analysis approach to systematically review and comprehensively evaluate the actual performance and underlying mechanisms of modified biochar in remediating soils contaminated with cadmium, arsenic, and lead. Focusing on the effects of various modified biochars on the speciation of soil heavy metals and on crop uptake and accumulation, we analyze their overall impacts on soil physicochemical properties, heavy metal bioavailability, and plant metal accumulation.

Based on this, subgroup analyses are conducted to compare the effects of biochar on soil available Cd, As, and Pb as well as on crop uptake under different experimental conditions. This allows us to identify modification pathways that are more effective in immobilizing heavy metals and reducing the risk of crop contamination.

Furthermore, correlation analysis is used to explore the intrinsic relationships among soil physicochemical indicators, available heavy metal contents, and plant heavy metal accumulation. This further elucidates the mechanisms by which modified biochar stabilizes and immobilizes heavy metals.

This study aims to provide a scientific reference for the safe utilization of heavy metal-contaminated farmland and for the quality control of agricultural products, thereby supporting the improvement of the soil ecological environment and the sustainable development of agriculture.

1.4.2. Research Content

This study first conducts a systematic literature search and in-depth analysis to comprehensively clarify the current research status, key bottlenecks, and knowledge gaps in the field of modified biochar for remediating soils contaminated with cadmium, arsenic, and lead. Based on this, the core direction and key focus of this study are precisely defined.

Next, following strict pre-established inclusion and exclusion criteria, the retrieved literature is screened and evaluated. Studies that do not meet the requirements are excluded. Valid data are extracted from the eligible studies and systematically organized.

Finally, using meta-analysis, a systematic quantitative investigation is carried out around the research theme. The specific core research contents are as follows.

1) Based on a meta-analysis of literature from databases, this study comprehensively and systematically evaluates the regulatory effects of modified biochar application on key soil physicochemical properties. Subgroup analyses are also conducted to examine how various grouping variables influence the effectiveness of modified biochar in reducing soil available Cd, As, and Pb contents. The key factors affecting the immobilization of these three heavy metals by modified biochar are identified, and the underlying mechanisms are thoroughly analyzed.

2) Based on the meta-analysis, this study focuses on how different soil physicochemical properties (e.g., soil type, organic matter content, and pH) and characteristics of modified biochar (e.g.,

feedstock, modification method, pyrolysis temperature, biochar pH, and application rate) affect the accumulation of cadmium, arsenic, and lead in different crop species and their various organs. This systematically reveals the patterns by which modified biochar regulates the transport and transformation of these three heavy metals in the soil-plant system.

3) Using meta-analysis, this study focuses on the changes in soil microbial biomass during the remediation of cadmium, arsenic, and lead contamination by modified biochar. Specifically, it investigates the effects of modified biochar application on the biomass of soil bacteria and fungi. Through correlation analysis, the relationships between changes in microbial biomass and various influencing factors are clarified. The effects of different biochar modification methods on the soil microecological environment during remediation are comprehensively evaluated. Ultimately, the key factors controlling microbial biomass changes in the remediation process of heavy metal-contaminated soils are identified.

1.4.3. Technical Route

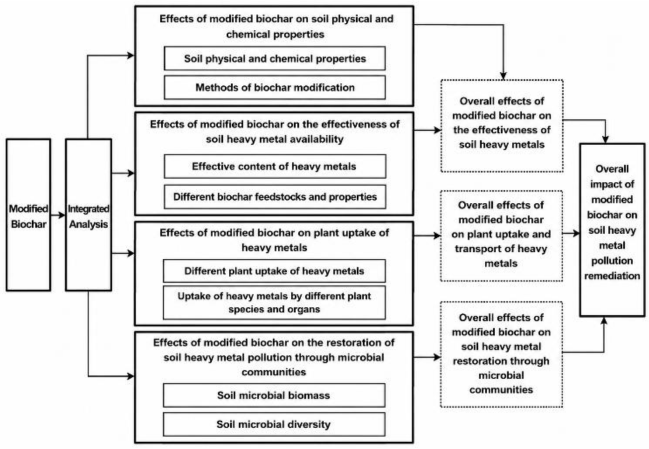

Figure 3 Figure of the Technical Route

2. MATERIALS AND METHODS

This study employs a meta-analysis approach to systematically quantify the remediation effects of straw-derived biochar, specifically its preparation processes and structural regulation methods, on heavy metal-contaminated soils. The goal is to clarify how different conditions influence the immobilization of soil heavy metals, the control of heavy metal accumulation in crops, and the soil microecological environment. By integrating data from published field trials, pot experiments, and laboratory incubation studies conducted across China, this analysis eliminates the heterogeneity of experimental conditions and the chance effects inherent in single studies. The findings will provide data support and a theoretical basis for the engineering application of straw-derived biochar in remediating heavy metal-contaminated soils.

2.1. Data Sources and Literature Search

This study systematically searched for relevant literature on the remediation of heavy metal-contaminated soils using straw-derived biochar. The searches were conducted in Chinese databases including China National Knowledge Infrastructure (CNKI) and Wanfang Data. The search keywords were: modified biochar, structural regulation, heavy metals, soil contamination, soil remediation, and immobilization. A combination of subject terms and free words was used. Additionally, the reference lists of the included studies were back-searched to identify any relevant studies that might have been missed[25].

The basic inclusion criteria for the literature were as follows. The straw-derived biochar treatment group and the control group were conducted under the same experimental conditions. Apart from the biochar treatment variable, all soil, environmental, and cultivation conditions were identical. The literature also had to contain detailed parameters of straw-derived biochar preparation, application rates, and corresponding experimental outcome data[26].

2.2. Data Extraction

From the literature that met the inclusion criteria after screening, this study systematically extracted relevant experimental data to build a standardized research database. For numerical data that could not be directly obtained from tables or text in the articles, Origin 2021 software was used to digitally convert and accurately extract values from graphs. This ensured completeness and accuracy of data extraction.

The extracted information covered four core dimensions.

First, basic experimental parameters. These included experimental location (country and city), experiment type (field, pot, or incubation), biochar application rate (% or t/ha), soil organic matter (SOM), cation exchange capacity (CEC), and soil organic carbon (SOC).

Second, basic soil information. This included soil heavy metal concentrations and soil enzyme activities.

Third, information on modified biochar. This involved feedstock type, application rate, modification method or modifier type, pyrolysis temperature, pH of modified biochar, and specific surface area.

Thus, a comprehensive database covering all experimental elements and research dimensions was established, providing a solid data foundation for the subsequent meta-analysis[27].

2.3. Data Extraction and Inclusion Criteria

To ensure data reliability, relevance, and the scientific validity of the meta-analysis results, this study established strict literature inclusion and exclusion criteria as well as data extraction rules. The details are as follows.

2.3.1. Inclusion criteria:

1) Relevant research focus: Studies must focus on the remediation of heavy metal-contaminated soils using modified biochar. Biochar must have undergone modification; studies using only unmodified pristine biochar were excluded.
2) Sound experimental design: Experiments must include a control group and treatment groups. The control group should receive either no biochar or unmodified biochar. Treatment groups should receive biochar modified under different conditions.
3) Complete indicator data: The literature must contain at least one type of core observation indicator.
4) Compliant data format: Means, standard deviations (SD), or standard errors (SE) must be reported, with at least three replicates. Data must be extractable from tables, text, or digitized graphs.
5) Study type restriction: Only field trials, pot experiments, and laboratory incubation studies (i.e., empirical research) are included. Simulation studies, theoretical analyses, reviews, comments, and patents are excluded[28].

2.3.2. Exclusion criteria:

1) Off-topic: Studies not on modified biochar remediation of soil cadmium contamination.

2) Design flaws: No clear control group, fewer than three replicates, or poorly controlled variables.
3) Missing data: Incomplete core indicators, or unclear modification conditions or application rates.
4) Duplicate data: For redundant data from the same study published in different journals or theses, only the most complete and longest-duration version is retained.
5) Logical or design errors: Obvious outliers, calculation errors, or serious experimental design flaws[29].

2.4. Data Processing and Analysis

The data analysis and processing workflow mainly includes effect size calculation, heterogeneity testing, model selection for pooled effect size estimation, confidence interval calculation, conversion of effect sizes to percentages, and subgroup analysis. All data processing was performed using Microsoft Excel 2021 for data organization, and Origin 2021 software was used to generate the relevant figures and tables.

2.4.1. Effect Size Calculation

Effect size is a metric that quantifies the magnitude of a treatment effect. In this study, the natural logarithm of the response ratio was used as the effect size. For the i-th study, the effect size $\ln RR_i$ was calculated as:

$$\ln RR_i = \ln\left(\frac{X_{ei}}{X_{ci}}\right) \quad (1)$$

where X_{ei} is the mean of the treatment group (amended with modified straw biochar), and X_{ci} is the mean of the control group (no biochar or unmodified biochar).

A value of $\ln RR_i<0$ indicates that modified biochar reduces the available content of soil heavy metals or the heavy metal content in plants (a negative effect); $\ln RR_i>0$ indicates an increase (positive effect); and $\ln RR_i=0$ indicates no effect.

The variance of each effect size, $V_{\ln RR_i}$, was used for subsequent weighted pooling and was calculated as:

$$V_{\ln RR_i} = \frac{SD_{ei}^2}{n_{ei}X_{ei}^2} + \frac{SD_{ci}^2}{n_{ci}X_{ci}^2} \quad (2)$$

where SD_{ei} and SD_{ci} are the standard deviations of the treatment and control groups, respectively, and n_{ei} and n_{ci} are the numbers of replicates in the treatment and control groups, respectively. If a study provided only the standard error (SE), it was converted to standard deviation using:

$$SD = SE \times \sqrt{n} \quad (3)$$

If a study reports soil organic matter (SOM) content, it should be converted to soil organic carbon (SOC) content to unify the indicator. The conversion formulas are:

$$SOC = SOM \times 0.58 \text{ or } SOM = SOC \times 1.724 \quad (4)$$

2.4.2. Heterogeneity Test and Model Selection

To determine whether effect sizes are consistent across studies, a heterogeneity test is required. Commonly used statistics include the Q statistic and the I^2 statistic.

$$Q = \sum_{i=1}^{k} W_i(Y_i - \overline{Y})^2 \quad (5)$$

where W_i is the weight of the i-th study (under the fixed-effect model, $W_i = 1/V_{\ln RR_i}$), $Y_i = \ln RR_i$ is the effect size of the i-th study, $\overline{Y}$ is the weighted mean effect size across all studies (see Section 2.4.3 for calculation), and k is the number of studies.

$$I^2=\frac{Q-(k-1)}{Q}\times 100\%\tag{6}$$

I² reflects the magnitude of heterogeneity and ranges from 0% to 100%. If $P\geq 0.05$ and $I^2<50\%$, the studies are considered homogeneous, and the fixed-effect model (FEM) is used for meta-analysis. If $P<0.05$ or $I^2\geq 50\%$, significant heterogeneity exists, and the random-effect model (REM) is used. For the random-effect model, the between-study variance τ^2 must be estimated, typically using the DerSimonian-Laird method.

$$\tau^2=\frac{Q-(k-1)}{C},C=\sum_{i=1}^{k} w_i-\frac{\sum_{i=1}^{k} w_i^2}{\sum_{i=1}^{k} w_i}\tag{7}$$

If the calculated τ^2 is negative, it is set to $\tau^2=0$. In this case, the random-effect model reduces to the fixed-effect model.

2.4.3. Pooled Effect Size and Confidence Interval

Under the fixed-effect model, the pooled effect size $\overline{Y}_{FE}$ is the weighted mean of the individual study effect sizes:

$$\overline{Y}_{FE}=\frac{\sum_{i=1}^{k} w_i Y_i}{\sum_{i=1}^{k} w_i},\text{where } w_i=\frac{1}{V_{\ln RR_i}}\tag{8}$$

Under the random-effect model, the weights are adjusted to $w_i^*=\frac{1}{V_{\ln RR_i}+\tau^2}$, and the pooled effect size $\overline{Y}_{RE}$ is:

$$\overline{Y}_{RE}=\frac{\sum_{i=1}^{k} w_i^* \ln RR_i}{\sum_{i=1}^{k} w_i^*}\tag{9}$$

The standard error of the pooled effect size, $SE(\overline{Y}_{RE})$, and its 95% confidence interval (CI) are:

$$SE(\overline{Y}_{RE})=\sqrt{\frac{1}{\sum_{i=1}^{k} w_i^*}}\tag{10}$$

$$95\%\ CI=\overline{Y}_{RE}\pm 1.96\times SE(\overline{Y}_{RE})\tag{11}$$

If the 95% confidence interval does not include zero, the pooled effect size is statistically significant at the $\alpha=0.05$ level.

2.4.4. Conversion of Effect Size to Percentage Change

To intuitively interpret the magnitude of the effect, the pooled effect size $\overline{Y}$ (i.e., $\overline{Y}_{FE}$ or $\overline{Y}_{RE}$, depending on the selected model) is converted to a percentage change:

$$\text{Percentage change}=(e^{\overline{Y}}-1)\times 100\%\tag{12}$$

A negative percentage change indicates a reduction in the treatment group relative to the control group, while a positive value indicates an increase.

2.4.5. Subgroup Analysis

To explore the influence of different factors (e.g., soil properties, biochar preparation conditions, experimental conditions) on remediation efficacy, subgroup analyses were conducted according to pre-defined grouping variables. These grouping variables included soil pH, soil texture, soil organic matter content, biochar pyrolysis temperature, modification method, biochar feedstock, application rate, and experimental duration.

The pooled effect sizes and their 95% confidence intervals were compared among subgroups, supplemented by between-group heterogeneity tests (e.g., the Qb statistic) to determine whether differences between subgroups were significant. If the confidence intervals of subgroups did not overlap and the between-group heterogeneity test gave $P<0.05$, the difference between subgroups was considered significant.

2.4.6. Sensitivity Analysis and Publication Bias Test

To ensure the robustness of the meta-analysis results, a sensitivity analysis was performed. This involved recalculating the pooled effect size after sequentially removing each individual study and observing whether the results changed significantly.

Publication bias was assessed using a funnel plot and Egger's test. If the funnel plot was symmetric and Egger's test gave a P value greater than 0.05, no significant publication bias was indicated.

3. META-ANALYSIS OF THE EFFECTS OF MODIFIED BIOCHAR ON SOIL PHYSICOCHEMICAL PROPERTI

3.1. Overall Effect of Modified Biochar on Soil Physicochemical Properties

Applying modified biochar significantly improves soil physicochemical properties. Overall, it effectively regulates soil pH, increases organic matter content, and enhances soil adsorption capacity. Quantitative analysis showed that compared to the control group without biochar, soil pH, soil organic carbon (SOC), and cation exchange capacity (CEC) all increased significantly ($p < 0.05$). The average increases were 10.27%, 36.53%, and 23.66%, respectively.

3.2. Effect of Modified Biochar on Soil pH

This study examined the effects of various factors on changes in soil pH. These factors included experiment site type, experimental duration, initial soil pH, soil texture, sampling depth, preparation conditions of modified biochar, and application rate. The heterogeneity analysis showed that the effect sizes within subgroups of the above factors exhibited significant heterogeneity. This indicates that all these factors are core variables causing differences in the regulatory effect of modified biochar on soil pH.

Different modification methods had significantly different effects on the ability of biochar to increase soil pH. Overall, the application of all modified biochars significantly raised soil pH ($p < 0.05$). Among them, thiourea-modified biochar showed the most prominent increase, raising soil pH by 25.83%. Alkali-modified and sulfur-modified biochar followed, with increases of 25.79% and 22.63%, respectively. In contrast, Fe modification, microbial modification, Ca modification, P modification, and Zn modification resulted in relatively small increases, all below 10%. The specific increases were 8.45%, 8.23%, 7.36%, 6.37%, and 5.56%, respectively.

In addition to the modification method, biochar pyrolysis temperature, application rate, and biochar pH are also key factors influencing changes in soil pH. The analysis showed that different pyrolysis temperatures and application rates all significantly increased soil pH ($p < 0.05$). The best effects were observed at application rates of 1%–2% and 2%–5%, with pH increases of 11.16% and 10.93%, respectively. In contrast, application rates of <1% and >5% gave relatively smaller increases of 9.44% and 7.62%.

Regarding pyrolysis temperature, the increase in soil pH generally rose with temperature. Biochars produced at <400°C, 400–499°C, 500–599°C, 600–699°C, and >700°C increased soil pH by 11.38%, 8.27%, 8.40%, 13.41%, and 21.08%, respectively. Notably, the <400°C group had few data points and a wide confidence interval. However, the overall trend indicates that higher pyrolysis temperatures lead to a greater increase in soil pH by modified biochar.

Furthermore, modified biochars with different pH values all significantly affected soil pH, with significant between-group heterogeneity ($p < 0.05$). After applying modified biochars with pH <7, 7–

8, 8–9, 9–10, and >10, soil pH increased by 7.5%, 8.05%, 8.65%, 17.43%, and 15.54%, respectively. Overall, the increase in soil pH enhanced with higher biochar pH, peaking at a biochar pH of 9–10, and then slightly declined above 10. This suggests that a higher biochar pH is not always better; selecting modified biochar with an appropriate pH range is more effective for regulating soil acidity.

For example, Liu Yang et al. [30] reported that biochar pH had the strongest direct positive effect on Pb remediation efficiency, indicating that an increase in pH helps immobilize Pb ions through precipitation or complexation, thereby improving remediation outcomes. Therefore, controlling biochar pH is not only key to improving soil pH but also an important pathway to enhance the potential for heavy metal remediation.

Regarding the effect of modified biochar on soil pH under different experimental conditions, the analysis showed that soil pH increased by 10.15% in pot experiments and 10.46% in field experiments, with no significant difference between the two ($p > 0.05$). For experimental durations of <7 days, 8–14 days, 15–30 days, 31–90 days, and >90 days, the increases in soil pH were 11.22%, 8.96%, 10.79%, 10.60%, and 3.33%, respectively. No significant differences were found among the duration groups ($p > 0.05$). This indicates that experiment type and duration have limited effects on the ability of modified biochar to increase soil pH, although a slight decline was observed under long-term conditions (>90 days).

The effect of modified biochar on soil pH varied under different soil conditions. In terms of initial soil pH, application of modified biochar significantly increased soil pH across all three acidity categories ($p < 0.05$), with increases of 14.75%, 11.06%, and 8.46%, respectively, and significant differences were found among the groups. Regarding soil texture, modified biochar significantly increased pH in all soil textures, with the increase in sandy soil being notably higher than in other soil textures.

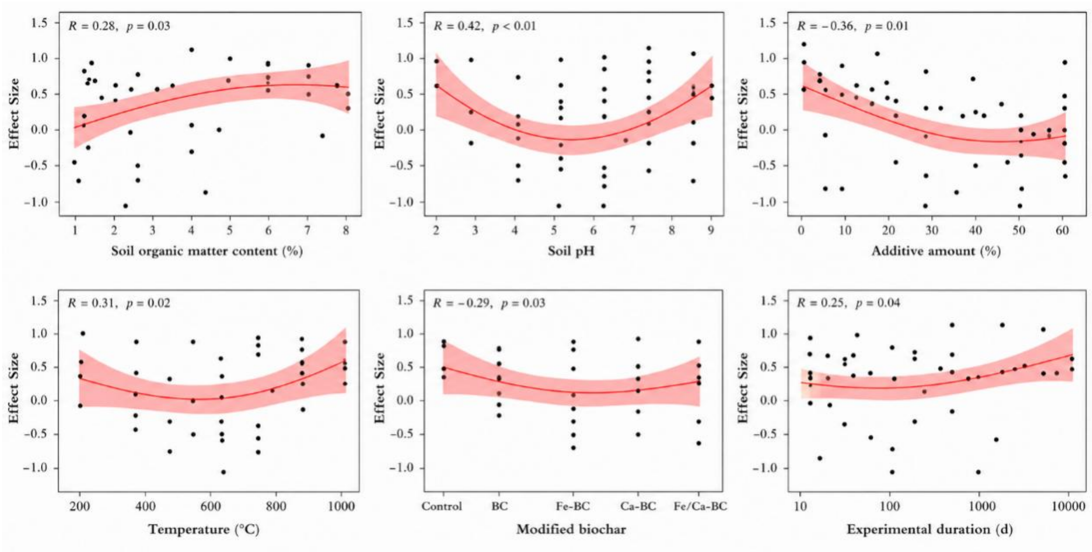

Figure 4 Effects of modified biochar on soil organic matter and pH

3.3. Effect of Modified Biochar on Soil SOC

Soil organic matter is a core indicator of soil fertility. It not only contains various carbon-containing organic compounds but also promotes mineral weathering and accelerates nutrient availability, thereby improving nutrient use efficiency. The analysis showed that compared to the control group, applying modified biochar significantly affected soil organic carbon (SOC) under different grouping conditions. According to the heterogeneity test results, the differences between subgroups of experiment type (e.g., pot vs. field) and soil sampling depth were not significant ($p > 0.05$). This indicates that these two factors are not the main moderators causing differences in SOC change.

Different modification methods exhibited significant differences in enhancing soil organic carbon (SOC) ($Qb = 1095.2$, $p = 0.001$). Specifically, microbial modification, S modification, Fe modification, and alkali modification increased SOC by 61.25%, 32.8%, 18.49%, and 11.55%, respectively. Microbial modification was particularly effective in improving organic matter, remediating heavy metal-contaminated and poor soils, and optimizing the microbial environment. In contrast, oxidation modification and Mn modification did not significantly increase SOC, possibly due to insufficient sample size. Further research on these modification methods is needed.

The pH, pyrolysis temperature, and application rate of different modified biochars all showed significant heterogeneity in their effects on SOC, indicating that these three factors are important moderators of SOC change.

Regarding application rate, when modified biochar was applied at <1.0%, 1.0–2.0%, 2.0–5.0%, and >5%, SOC increased significantly by 13.71%, 31.62%, 35.18%, and 29.21%, respectively. The application rate of 2.0–5.0% gave the best effect, with an increase exceeding 35%.

Regarding pyrolysis temperature, modified biochars produced at different temperatures all significantly increased SOC. The increases for the temperature groups <400°C, 400–499°C, 500–599°C, and 600–699°C were 16.17%, 39.35%, 22.85%, and 27.30%, respectively. Biochar produced at 400–499°C showed the most prominent increase, nearly 40%.

Regarding biochar pH, modified biochars with different pH ranges all significantly increased SOC, with significant between-group differences ($p < 0.05$). When biochar pH was <7, 7–8, 8–9, 9–10, and >10, SOC increased by 21.15%, 22.06%, 22.43%, 46.38%, and 19.01%, respectively. Thus, modified biochar with a pH of 9–10 exhibited the most significant improvement in SOC, while the effect declined when pH was too high (>10).

Regarding experiment type, both pot and field conditions showed that applying modified biochar effectively increased soil organic carbon (SOC). SOC increased by 30.4% in pot experiments and 28.01% in field experiments, with similar effects between the two.

Regarding experimental duration, the effect of modified biochar on SOC varied over time. SOC increased by 34.69%, 44.62%, 15.48%, 35.05%, and 43.71% at 0–7 days, 8–14 days, 15–30 days, 31–90 days, and >90 days after application, respectively. The most significant increases (over 43%) occurred during the 8–14 day and >90 day periods.

Overall, modified biochar significantly increases soil SOC, especially under microbial modification and within the optimal pH range (9–10). The increase in SOC not only helps improve soil structure and nutrient supply but also enhances soil adsorption and immobilization of heavy metals.

A meta-analysis by Hanyi Liu et al. [31] showed that modified biochar reduced soil available Cd by an average of 65.01% and Cd content in the edible parts of plants by 70.72%. Lignocellulosic biochar and organic modification were particularly effective. This suggests that increasing SOC content not only aids soil fertility restoration but may also indirectly improve Cd remediation efficiency by enhancing organic matter complexation with Cd.

3.4. Effect of Modified Biochar on Soil CEC

Different modification methods exhibited highly significant differences in enhancing soil cation exchange capacity (CEC) ($Qb = 455.76$, $p = 0$). According to the analysis, most modification methods significantly increased soil CEC. Specifically, Mn modification, Fe modification, thiourea modification, acid modification, and Ca modification increased soil CEC by 132.69%, 46.33%, 46.47%, 37.7%, and 10.0%, respectively. Among these, Mn-modified biochar showed the most prominent increase, exceeding 130%. It is worth noting that P-modified biochar significantly reduced soil CEC, with a decrease of 80.95%.

Application rate, pyrolysis temperature, and biochar pH all significantly influenced the effectiveness of modified biochar in increasing soil CEC.

Regarding application rate ($Qb = 48.78$, $p < 0.05$), when the addition rate was <1.0%, 1.0–2.0%, 2.0–5.0%, and >5.0%, CEC increased by 5.78%, 55.72%, 29.42%, and 37.11%, respectively. The greatest increase (55.72%) occurred at 1.0–2.0%.

Regarding pyrolysis temperature ($Qb = 90.66$, $p < 0.05$), biochar produced at >700°C showed the most prominent increase in CEC, reaching 74.56%. The increases at 400–499°C, 500–599°C, and 600–699°C were 19.56%, 27.21%, and 18.38%, respectively.

Regarding biochar pH ($Qb = 458.5$, $p < 0.05$), when biochar pH was 8–9, 9–10, and 7–8, CEC increased significantly by 7.45%, 33.05%, and 11.31%, respectively. However, when pH >10, CEC significantly decreased by 7.32%. When pH <7, no significant effect was observed, possibly due to the small sample size.

Under different experimental conditions, modified biochar consistently affected soil CEC. In terms of experiment type, both pot and field experiments showed significant increases in soil CEC after modified biochar application, with increases of 12.6% and 44.17%, respectively. The effect was more pronounced under field conditions.

In terms of experimental duration, the increase in CEC exhibited a phased pattern. The largest increase (87.3%) occurred within 0–7 days after application. At 15–30 days and 31–90 days, the increases were 29.0% and 31.36%, respectively, which remained significant. However, after more than 90 days, the effect of modified biochar on increasing soil CEC was no longer significant.

The increase in soil cation exchange capacity (CEC) by modified biochar varied significantly under different soil conditions. Regarding soil pH, applying modified biochar significantly increased CEC in acidic (pH < 6.5), neutral (6.5–7.5), and alkaline (pH > 7.5) soils ($p < 0.05$), with increases of 13.04%, 25.23%, and 48.08%, respectively. The effect showed an increasing trend with higher soil pH. Regarding soil texture, applying modified biochar significantly increased CEC in sandy soil, loam, and clay soil by 39.0%, 15.8%, and 11.07%, respectively. The increase was most prominent in sandy soil. This may be because the application of modified biochar significantly increased the amount of soil colloids, leading to the largest CEC increase in soils with low clay content.

In summary, modified biochar significantly increases soil CEC, with particularly prominent effects in alkaline soils and sandy soils. This indicates that modified biochar helps enhance soil fertility retention and ion exchange capacity. This change is also highly important for heavy metal remediation. Mandal et al. [1] pointed out that biochar produced at high pyrolysis temperatures (>450°C) has a large specific surface area and a high degree of aromaticity. When combined with iron-manganese modification, it can effectively reduce the mobility of arsenic (As) and convert it into insoluble forms. Therefore, increasing CEC not only helps improve soil chemical properties but may also further enhance remediation efficacy by strengthening the adsorption and immobilization capacity for heavy metals such as As.

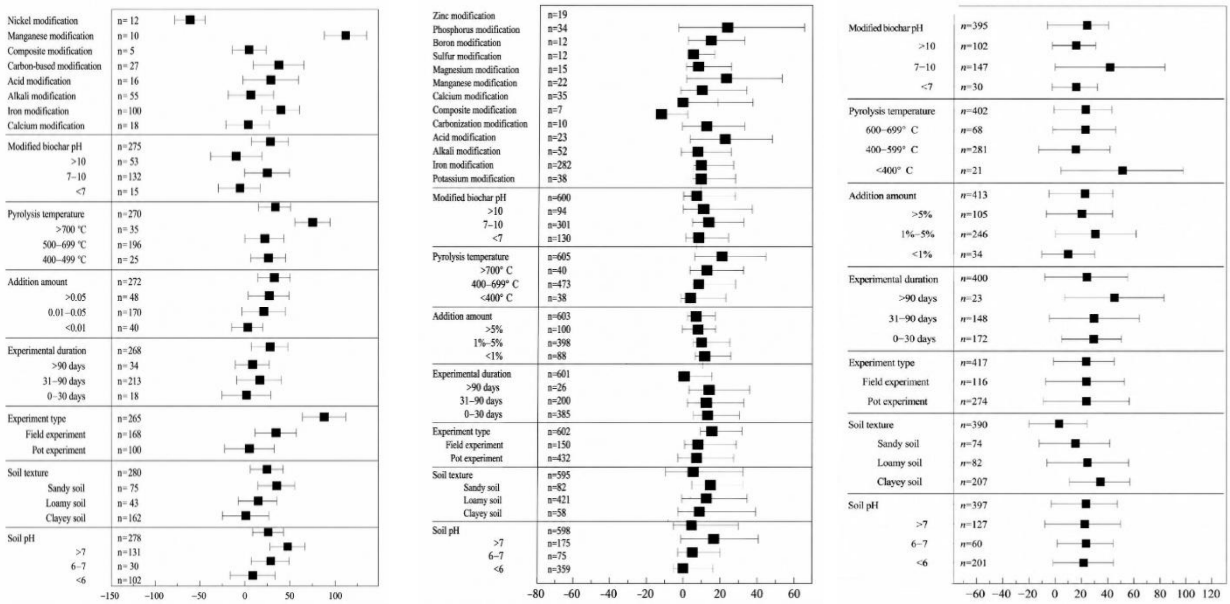

Figure 5 Forest plot of subgroup analysis for the effect of different modification methods on soil pH

4. REMEDIATION EFFECTS AND MECHANISMS OF MODIFIED BIOCHAR ON HEAVY METAL-CONTAMINATED SOILS

4.1. Remediation Effects and Regulatory Mechanisms of Modified Biochar on Lead (Pb)-Contaminated Soils

Based on the above analysis of changes in soil pH, SOC, and CEC, biochar pH, ash content, and surface functional groups are key factors affecting Pb immobilization. Data analysis shows that biochar pH has the strongest direct positive effect on Pb remediation efficiency. This is highly consistent with the finding that modified biochar generally increases soil pH (by up to 25.83%). A high pH environment promotes the formation of Pb(II) hydroxides or carbonates, while mineral components in ash (e.g., phosphates and carbonates) further fix Pb through precipitation or complexation.

Pyrolysis temperature significantly affects soil pH and SOC. Biochar produced at high temperature (>700°C) increased soil pH by 21.08%, while biochar produced at 400–499°C increased SOC by 39.35%. Data show that the best remediation effect occurs when ash content >40%. High-temperature pyrolysis not only increases ash content but also enhances the stability of the carbon (skeleton), favoring Pb adsorption. A pyrolysis time of 2–4 h balances functional group retention and structural stability. This condition corresponds to the 27.21% increase in CEC observed for biochar produced at moderate temperature (500–599°C), suggesting that increased CEC may also participate in Pb fixation through ion exchange.

A biochar application rate of 2%–5% gives the best increases in pH (10.93%) and SOC (35.18%). The optimal application rate for Pb remediation is 4%–6%. Excessively high rates may damage soil structure. Therefore, an appropriate application rate not only optimizes soil physicochemical properties but also maximizes Pb immobilization efficiency, and should be adjusted according to pollution level and soil type.

4.2. Remediation Effects and Regulatory Mechanisms of Modified Biochar on Cadmium (Cd)-Contaminated Soils

The feedstock type significantly influences Cd remediation efficiency. Lignocellulosic biochar reduced soil available Cd most effectively, with a decrease of 96.34%. Herbaceous biochar showed the greatest reduction in Cd content in the edible parts of plants, reaching 100.53%. This indicates that feedstock type is an important regulatory factor. Lignocellulosic biochar is more suitable for Cd immobilization in soil, while herbaceous biochar has an advantage in reducing Cd translocation into plants.

Modification methods also significantly affect Cd remediation. Acid-alkali modification and organic modification were particularly effective in reducing Cd availability, with decreases of 112.03% and 119.53%, respectively. Regarding mechanisms, acid-alkali modification enhances Cd adsorption by altering the surface charge and functional group status of biochar. Specifically, alkali modification increased soil pH by 25.83%, and acid modification increased soil CEC by 37.7%. Organic modification increases oxygen-containing functional groups that complex Cd. In addition, microbial modification increased soil SOC by 61.25%, potentially enhancing organic matter fixation of Cd through microbial action. Fe modification increased CEC by 46.33%, suggesting it can fix Cd through enhanced cation exchange. Mn modification increased CEC by as much as 132.69%, showing significant potential for Cd adsorption.

Application rate is a key factor influencing Cd remediation efficiency. Data show that an application rate of 2%–3% reduces soil available Cd by 76.94% and Cd content in plants by 88.88%. Regarding soil physicochemical responses, the application rate of 1%–2% gives the greatest increase in CEC (55.72%), while 2%–5% gives the greatest increase in SOC (35.18%). Therefore, an application rate of 2%–3% effectively improves soil adsorption capacity while avoiding potential negative effects of excessive application.

Soil texture also modulates Cd remediation efficiency. Modified biochar increases SOC most significantly in clay soil (36.10%) and CEC most significantly in sandy soil (39.0%). This suggests that Cd remediation strategies should differ by soil texture. In clay soil, the complexation of Cd by organic matter should be fully utilized. In sandy soil, enhancing cation exchange capacity should be emphasized.

Initial soil pH also affects Cd remediation. Modified biochar increases SOC most in neutral soil (30.52%) and CEC most in alkaline soil (48.08%). Under alkaline conditions, Cd tends to form precipitates. Under neutral conditions, Cd is more readily adsorbed by organic matter. Therefore, by regulating soil pH and SOC, modified biochar indirectly reduces Cd bioavailability. This is consistent with the finding that modified biochar reduces soil available Cd by an average of 65.01%.

4.3. Remediation Effects and Regulatory Mechanisms of Modified Biochar on Arsenic (As)-Contaminated Soils

Pyrolysis temperature determines the fundamental properties for As immobilization. Biochar produced at high temperature (>450°C) has a large specific surface area, a high degree of aromaticity, and abundant mineral phases (e.g., $CaHPO_4$, $CaCO_3$), leading to better As fixation. Biochar pyrolyzed at >700°C increased soil pH by 21.08% and CEC by 74.56%, creating favorable conditions for As adsorption and precipitation.

Feedstock type also influences remediation outcomes. Corn straw and sewage sludge biochars significantly reduced As content in rice, whereas soybean straw and rice straw biochars were less effective. This may be related to differences in silicon, iron, and other elements in the feedstocks, which can modify biochar surface properties and thus affect As adsorption.

Modification methods enhance As immobilization. Iron modification reduces As mobility through iron solid-phase adsorption and iron-manganese oxides. Although Fe modification increased soil pH only modestly (8.52%), it significantly raised CEC (46.33%), suggesting that its mechanism mainly involves ion exchange and surface complexation. Mn modification increased CEC by as much as 132.69%, implying that Mn oxides enhance As adsorption by increasing surface charge. Hydroxyapatite-zeolite composite modification converts As into insoluble forms through calcium binding. In addition, the formation of iron films can physically block As entry into rice roots, which is an added benefit of biochar in improving the rhizosphere environment.

A higher application rate is not always better. A low dose (0.5%–2%) effectively reduces As content in rice. However, once the rate exceeds 3%–5%, it may instead stimulate the activity of Fe(III)/As(V)-reducing bacteria, leading to re-activation of previously immobilized As. At an application rate >5%, the increase in soil pH drops to 7.62%, and although CEC still increases by 37.11%, the release of soluble organic matter may enhance microbial activity. Therefore, for As-contaminated soil, application rates must be strictly controlled to avoid secondary risks caused by changes in the soil microecological environment.

Soil properties are closely related to As speciation transformation. Modified biochar increases CEC most significantly in alkaline soils, where As mainly exists as anionic species such as AsO_4^{3-}. An increase in CEC can enhance As adsorption by providing more positively charged sites. Meanwhile, microbial modification increases SOC by 61.25%, but whether organic matter competitively adsorbs or complexes As remains unclear and requires further study. In summary, targeted remediation of As-contaminated soils can be achieved by selecting high-temperature pyrolysis, matching suitable feedstock and modification methods, and strictly controlling the application rate.

5. CONCLUSION

Modified biochar significantly improved soil physicochemical properties: pH, SOC, and CEC increased by 10.27%, 36.53%, and 23.66% on average. Thiourea modification raised pH the most (25.83%); microbial modification increased SOC most (61.25%); Mn modification boosted CEC by 132.69%. Optimal conditions: biochar pH 9–10 (46.38% SOC increase), pyrolysis temperature >700°C (21.08% pH increase, 74.56% CEC increase), application rate 1%–2% (55.72% CEC increase) or 2%–5% (35.18% SOC increase).

Modified biochar effectively immobilized all three heavy metals, with differing mechanisms and optima. Pb: best with ash >40%, high temperature (>700°C), and 4%–6% application rate, via precipitation and complexation. Cd: lignocellulosic feedstock, organic modification, and 2%–3% application rate reduced soil available Cd by 76.94% and plant Cd by 83.78%. As: high temperature (>450°C) combined with Fe/Mn modification and 0.5%–2% application rate was most effective; rates >3%–5% risk As re-activation.

Soil properties strongly influenced remediation. Alkaline soils showed the highest CEC increase (48.08%); sandy soils had a greater CEC increase (39.0%) than other textures; clay soils showed the greatest SOC increase (36.10%). Modified biochar and application strategies should be tailored to soil conditions.

Modified biochar synergistically enhanced electrostatic adsorption, ion exchange, complexation, and precipitation of heavy metals by raising pH, SOC, and CEC. Microbial modification improved the soil microecology, but excessive application or improper modification may cause secondary risks.

In summary, modified biochar is an efficient material for remediating heavy metal-contaminated soils. Optimizing feedstock, pyrolysis temperature, modification method, and application rate for specific heavy metals, soil types, and remediation goals is key to engineering application. This study provides data and theoretical support for the precise regulation of straw-derived biochar.

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