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Review Article

Sustainable Valorization of Used Biochar for Hexavalent Chromium Removal from Wastewater and Soil Fertility Enhancement

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Abstract

Environmental pollution from wastewater and soil contamination remains a critical global concern, with current treatment methods often facing limitations in scalability, cost, or environmental safety. Biochar, a carbon-rich material derived from biomass pyrolysis, has emerged as a sustainable adsorbent for heavy metals and organic pollutants. While its use in environmental remediation is well-established, the fate and reuse of spent biochar have received limited attention. This comprehensive review explores the untapped potential of used biochar, particularly for the removal of hexavalent chromium (Cr(VI)) from wastewater and its role in enhancing soil fertility. We critically analyze current practices, mechanisms of Cr(VI) removal using spent biochar, regeneration techniques, and field applications, while highlighting circular economy frameworks that promote resource efficiency. The study integrates empirical evidence from recent case studies and offers policy recommendations to support large-scale implementation. This work is the first to provide an integrative review of the reuse of spent biochar with a dual focus on wastewater treatment and soil enhancement, underpinned by a circular economy perspective. It addresses critical research gaps by evaluating regeneration techniques, post-use functionality, and practical field applications, thereby positioning spent biochar as a viable, low-cost, and eco-friendly alternative in environmental management systems.

Keywords: Environmental remediation; regeneration materials; toxic metals; utilization of waste materials; wastewater treatment

1. Introduction

Environmental degradation is a growing global concern, with water and soil pollution identified as some of the most urgent challenges. Increasing contamination from industrial, agricultural, and municipal activities poses significant risks to ecosystems and human health. Annual wastewater production has reached 359.4 billion cubic meters, with 63% being collected and 52% treated (Du Plessis, 2022). However, approximately 48% of wastewater is discharged untreated into the environment (Jones et al., 2021). Similarly, soil pollution is a critical issue, with economic impacts reported in various regions. For example, a recent study estimated that soil contamination in Luxembourg alone could cost between 85 and 149 million euros (Espinoza-Tofalos et al., 2025).

This study focused on Cr(VI) impact on water and soil, Cr(VI) is considered a highly toxic pollutant, particularly harmful to humans and ecosystems, even at very low concentrations. It is classified as a non-threshold toxin along with Pb, Cd, and Hg, meaning it can cause harm at any exposure level (Rahman & Singh, 2019). It is recognized as a Group 1 carcinogen by the International Agency for Research on Cancer (IARC), indicating confirmed carcinogenic effects in humans. Cr(VI) exhibits more severe health effects compared to its trivalent form (Cr(III)), including cancer, DNA damage, and immune system disruption, while also being more mobile and bioavailable in the environment (Chiu et al., 2010; Permenter et al., 2011; S. Singh et al., 2022). In addition to its high toxicity, Cr(VI), along with Pb and Cd, is frequently detected in environmental and biological samples at toxic levels, contributing to its reputation as one of the most problematic heavy metals in terms of environmental contamination and health risk (S. Singh et al., 2022).

Due to the negative impacts of contaminated soil and water, numerous researchers have explored various physical, biological, and chemical methods to address these issues. One such biological approach, phytoremediation, has demonstrated potential in removing pollutants from water and soil, offering a simple, low-cost solution (Jaswal et al., 2022). However, this method requires a long period to achieve effective results, and not all plants are classified as hyperaccumulators. Moreover, there is a significant risk involved, as the plants used in this process can be consumed by humans, posing potential health threats. In contrast, physical methods, such as filtration, can only remove larger particles and are ineffective at filtering heavy metals or other small pollutants from wastewater. Additionally, physical methods cannot be applied to soil. On the other hand, chemical methods, while effective, may generate secondary chemical pollutants, creating new environmental challenges.

Due to the limitations of various methods, numerous studies have highlighted adsorption as a low-cost, fast, and effective technique for pollutant removal from wastewater (I. Ali et al., 2012; De Gisi et al., 2016; Rashid et al., 2021). This method has been shown to efficiently remove both organic and inorganic pollutants. Biochar has emerged as a promising adsorbent due to its unique characteristics, including a high surface area, large pores, rich functional groups, and the fact that it does not require chemical reagents like activated carbon. Studies have demonstrated that biochar and its modifications can effectively reduce contaminants such as Fe and Mn from acid mine drainage (Wibowo, Safitri, et al., 2025), Cr(VI) (Wibowo, Anwar, Safitri, Setiawan, et al., 2025) and highly toxic metals like Cd, Hg and Pb (Wibowo, Anwar, Safitri, Surya, et al., 2025). Furthermore, biochar has successfully removed heavy metals and persistent organic pollutants, as well as improved the physicochemical properties of soil.

Although biochar has demonstrated significant benefits for water and soil remediation, there are currently no reported case studies or industrial applications that utilize biochar at the field or industrial scale. Most studies have primarily focused on the preparation and performance testing of biochar for improving water and soil quality, with limited research on the post-treatment reuse of used biochar. This paper aims to be the first comprehensive review to explore the potential reuse of post-treatment biochar for wastewater treatment and soil remediation. It will provide a detailed examination of the sources of biochar waste, the mechanisms of pollutant removal in wastewater and soil, a circular economy analysis, and case studies from highly reputable journals. Furthermore, this study will offer recommendations for future research, identify limitations, and provide a policy brief to accelerate the implementation of this method.

2. Methods

This review was conducted to synthesize current knowledge on the reuse of spent biochar for hexavalent chromium (Cr(VI)) removal from wastewater and for soil fertility enhancement. A comprehensive literature search was performed using multiple scientific databases, including Web of Science, Scopus, ScienceDirect, and Google Scholar, to identify peer-reviewed articles published between 2010 and 2025. The keywords used included: *biochar reuse*, *spent biochar*, *biochar regeneration*, *Cr(VI) removal*, *biochar in wastewater treatment*, *soil amendment*, and *circular economy biochar*. Only English-language articles published in peer-reviewed journals were considered. Priority was given to studies reporting experimental data, real-world applications, regeneration methods, and field-scale implementations of used biochar. Review articles were used to supplement background information and cross-verify findings.

Articles were screened based on relevance, novelty, methodological clarity, and scientific rigor. Data were extracted regarding biochar feedstock, pyrolysis conditions, pollutant types, removal mechanisms, regeneration approaches (physical, chemical, biological), soil effects, and case study outcomes. Findings were then thematically categorized and critically analyzed to identify recent trends, emerging technologies, performance limitations, and knowledge gaps. This review adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and reproducibility.

3. Result and Discussion

3.1. Biochar Waste: Sources, Uses, and Post-Use Challenges

Biochar, a carbon-rich byproduct of biomass pyrolysis, has gained significant attention for its multifaceted applications in agriculture and environmental remediation. Its physicochemical properties—particularly high surface area, porosity, and cation exchange capacity (CEC) contribute to its effectiveness as a soil enhancer and adsorbent for pollutants (Qiu et al., 2022; X. Xiao et al., 2018). As its use becomes more widespread, the generation of biochar waste, particularly after it has fulfilled its initial functional roles, introduces complex challenges regarding its environmental management and sustainability. This section delves into the origins of biochar waste, its conventional applications, and the pressing concerns surrounding its post-use handling and disposal.

The primary sources of biochar waste are rooted in its dominant applications: soil amendment and environmental remediation. In agricultural contexts, biochar is extensively applied to improve soil fertility, increase nutrient retention, enhance microbial activity, and ameliorate soil structure (Khan et al., 2021; Premalatha, Bindu, et al., 2023). These benefits translate into heightened crop productivity and more efficient use of agricultural inputs. Moreover, its application has been associated with significant reductions in greenhouse gas emissions, especially nitrous oxide (N_2O), with meta-analyses showing reductions of up to 49% (Joseph et al., 2021; Schmidt et al., 2021). This not only promotes nitrogen bioavailability but also supports improved nitrogen use efficiency, essential for sustainable farming systems (Liang et al., 2021).

Beyond agriculture, biochar has demonstrated notable efficacy in environmental remediation. It serves as a powerful adsorbent for both organic and inorganic pollutants due to its mineral constituents and structural characteristics. Studies have consistently shown that biochar can immobilize heavy metals and degrade organic contaminants, thereby reducing their mobility and bioavailability in polluted soils and waters (Gusiatin & Rouhani, 2023; Liang et al., 2021; Lu et al., 2020; Xu et al., 2017). These attributes make biochar an attractive material for rehabilitating contaminated environments, particularly in areas burdened by industrial discharge and mining activities. The widespread adoption of biochar in such remediation efforts contributes significantly to its eventual saturation with pollutants, leading to the generation of "spent" or used biochar.

Despite these diverse and beneficial uses, the accumulation of spent biochar raises serious environmental concerns. As biochar absorbs and retains pollutants over time, particularly heavy metals and persistent organic compounds, it can potentially transform from a remediation asset into a source of secondary pollution. Studies have highlighted the potential for contaminant leaching from spent biochar, especially when it is applied in degraded soils or regions with high leaching potential (Hilber et al., 2017; Rahim et al., 2022). Such risks underline the importance of conducting comprehensive risk assessments before large-scale deployment of used biochar in sensitive ecosystems (Blenis et al., 2023; Zhou, 2024). Moreover, finding sustainable disposal routes for biochar saturated with hazardous substances remains a critical issue, with current practices often lacking the infrastructure or guidelines necessary to prevent unintended environmental harm (Liang et al., 2021; Zhou, 2024).

To address these challenges, several post-use management strategies have been proposed. A circular bioeconomy framework encourages the reuse and recycling of biochar to prolong its functional life while minimizing waste. In agricultural systems, used biochar can still provide structural benefits to soils, including enhancing aeration and cation exchange capacity, even after its adsorption capacity has declined (Bolan et al., 2021; W. Wang et al., 2023a; Yaashikaa et al., 2020). Its continued incorporation into soils supports organic carbon enrichment and acid-neutralizing effects, contributing to long-term soil health and carbon sequestration (Mawalla & Gülser, 2025; Vilakazi et al., 2023; Warzukni et al., 2022).

In environmental remediation, the reuse of biochar is likewise being explored. Even when saturated, biochar can still immobilize certain contaminants and maintain partial effectiveness in polluted environments (Bhardwaj et al., 2022; Y. Ding et al., 2016; Domingues et al., 2017). Its multifunctionality provides a rationale for its strategic deployment in multilayer remediation processes or in combination with other materials to prolong its environmental utility.

Another emerging avenue for biochar waste valorization is its integration into engineered materials. Innovative research has demonstrated the feasibility of incorporating biochar into composite products such as construction materials, biodegradable plastics, and packaging components (Rajamani et al., 2023; X. Yuan et al., 2024). These applications not only divert biochar from waste streams but also leverage its structural integrity and thermal properties to enhance product performance (Tusar et al., 2023). Such strategies offer a dual benefit: reducing waste while promoting material circularity in industries beyond agriculture and remediation.

Nevertheless, these opportunities must be tempered by ongoing concerns regarding safety and regulatory oversight. The heterogeneity of feedstocks used in biochar production contributes to varying chemical compositions, some of which may introduce harmful elements into receiving environments if not properly managed (Ippolito et al., 2020). As such, comprehensive post-production characterization and standardized quality controls are imperative. Regulatory frameworks tailored to different biochar applications, especially those involving food production or environmental exposure, are urgently needed to ensure safety and efficacy across diverse use cases.

Thus, while biochar continues to prove valuable in agriculture and environmental management, its eventual transition into waste requires deliberate attention. The sustainability of biochar-based systems hinges not only on its initial effectiveness but also on how it is handled after use. Strategies that emphasize reuse, circular material design, and regulatory control can help mitigate the risks associated with spent biochar while optimizing its environmental contributions. Continued interdisciplinary research and policy innovation will be essential to harness the full potential of biochar without compromising ecological integrity or public health.

3.2. Recent Trends in Regeneration of Used Biochar

As the use of biochar expands in environmental remediation and soil management, the issue of managing spent or used biochar has gained increasing attention. Once biochar becomes saturated with pollutants or loses some of its initial properties due to prolonged exposure in soil or wastewater systems, its continued application becomes limited unless it undergoes regeneration. Recent advancements in physical, chemical, and biological regeneration methods (**Figure 1**) aim to restore or enhance the functional characteristics of used biochar, thereby extending its lifecycle, improving sustainability, and aligning with circular economy objectives. However, challenges remain in ensuring cost-effectiveness, safety, and environmental compatibility of these techniques, pointing to key areas where further study is urgently needed.

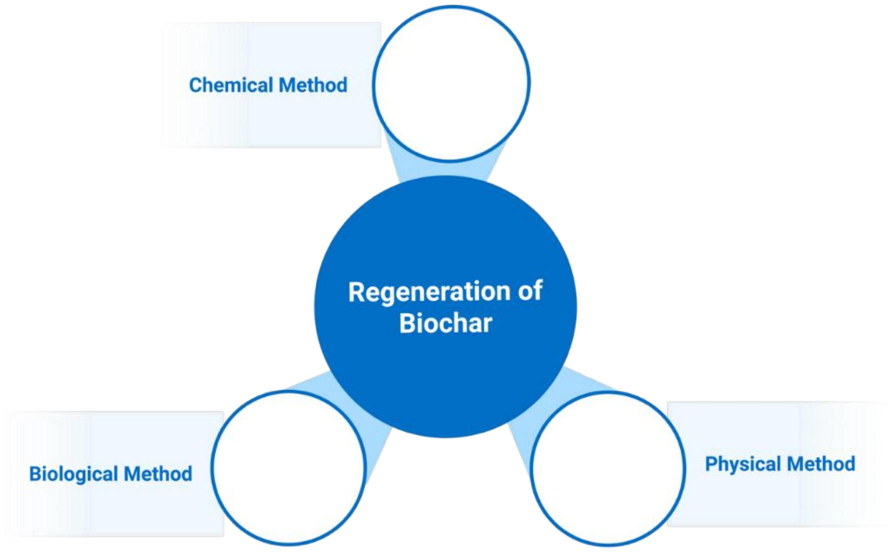

Figure 1. General methods in regeneration of biocahar

Physical regeneration techniques focus primarily on restoring the porosity and surface area of used biochar, which are often diminished due to pore blockage by adsorbed substances. Thermal treatment is one of the most common methods, where spent biochar is reheated at moderate to high temperatures under controlled conditions to desorb contaminants and reopen clogged pores. This method has shown success in reactivating the adsorptive capacity of biochar, particularly in heavy metal-laden materials. However, the energy demands of thermal regeneration, especially at higher pyrolysis temperatures, raise concerns regarding its environmental and economic sustainability. Alternative physical approaches such as ultrasound treatment and microwave irradiation have also been explored to promote pore cleaning and surface renewal, though these remain largely in the experimental phase. More research is needed to evaluate the scalability, energy efficiency, and long-term effectiveness of these physical regeneration methods under diverse environmental conditions. Thermal treatment effectively restores biochar's adsorption properties. For example, alkali-activated biochar achieved a surface area of ~2330 m^2/g and ciprofloxacin adsorption capacity of ~550 mg/g. A novel carbothermal shock technique showed promise for regenerating biochar quickly while maintaining structural integrity (Hong et al., 2024). In other side, ultrasound treatment has shown potential to enhance surface renewal and adsorption by cavitation effects, although further studies are needed to optimize performance (J. Wang et al., 2022).

Chemical regeneration techniques offer another promising pathway for restoring used biochar. These involve the use of acids, bases, or salt solutions to dissolve or displace adsorbed contaminants, thereby renewing the reactive surface sites. Regeneration using acid and base treatments (e.g., HCl, NaOH) is effective but carries environmental risks such as residual reagent leaching and structural degradation (Ahmed et al., 2016). Acid washing, particularly with dilute hydrochloric or nitric acid, has been found effective in removing heavy metals and restoring surface functionality. Similarly, alkaline solutions such as sodium hydroxide have been used to desorb organic contaminants and increase surface negative charge. While chemical methods can be highly effective, they pose potential risks such as secondary pollution, leaching of residual reagents into the environment, and degradation of biochar structure with repeated use. Therefore, optimization of chemical concentrations, contact time, and post-treatment washing protocols is critical to minimize adverse effects and ensure safe reuse. There is a growing interest in exploring greener chemical alternatives, such as the use of bio-based acids or natural complexing agents, which could reduce environmental risks while maintaining efficacy.

Biological regeneration represents an emerging and environmentally friendly approach that leverages microbial processes to rejuvenate spent biochar. Composting with biochar supports microbial degradation of contaminants, leading to biochar–humus complexes that benefit soil health. However, microbial mechanisms and byproduct profiles still need thorough investigation (W. Wang et al., 2023b). Studies highlight that biochar can support mycorrhizal fungi and microbial communities that naturally facilitate detoxification and nutrient cycling, indicating synergistic benefits with biological regeneration approaches (Ennis et al., 2012). Certain bacteria and fungi have shown the ability to degrade organic pollutants adsorbed on biochar surfaces or to immobilize heavy metals through biotransformation. These microbial consortia can restore biochar functionality without harsh chemical inputs, making the process more sustainable and compatible with natural ecosystems. In composting systems, for example, the integration of used biochar into organic matter piles not only supports microbial degradation of contaminants but also leads to the formation of biochar–humus complexes that can further improve soil health. Although promising, biological methods require more extensive study to understand the specific microbial communities involved, the rates of degradation, and the influence of environmental variables such as moisture, temperature, and pH. Additionally, concerns about the potential accumulation of toxic byproducts during microbial regeneration need to be carefully assessed.

A critical gap in the current knowledge is the comparative assessment of these regeneration techniques across various types of used biochar and contaminant profiles. Most existing studies focus on individual regeneration methods under controlled laboratory conditions, which do not fully capture the complexities of field environments. Integrated approaches that combine physical, chemical, and biological regeneration may offer synergistic benefits, but empirical data on their effectiveness, environmental impacts, and cost-efficiency remain limited. A comprehensive review emphasized that regeneration effectiveness varies significantly with contaminant type and biochar properties, and field-scale studies are scarce. Integrated approaches combining physical, chemical, and biological techniques are promising but underexplored (Shrivastava et al., 2024). Economic analysis shows regeneration feasibility is tightly linked to raw material costs and energy inputs, reinforcing the need for low-energy alternatives like carbonthermal shock or microbial routes (Ahmed et al., 2016). Moreover, the development of decision-making frameworks or guidelines to select appropriate regeneration methods based on biochar type, usage history, and intended reuse context is still lacking.

Thus, recent trends in used biochar regeneration reflect a growing commitment to sustainable resource use and environmental protection. Physical, chemical, and biological methods each present distinct advantages and limitations, and their continued development will be essential for optimizing biochar reuse strategies. Future research should prioritize field-scale validation, long-term performance monitoring, and the innovation of low-cost, environmentally sound regeneration technologies that support the full integration of biochar into circular systems. Table 1 showed the several studies related with the biochar regeneration and their performances.

Table 1. Modification biochar and their performance

Raw Materials	Modification of Biochar	Regeneration Methods	Adsorption Performance/Regeneration	Ref.
White tea residue	Magnetic modification with Fe oxides	EDTA-assisted desorption	Pb(II): 81.6 mg/g; Cd(II): 38.6 mg/g; ~54% capacity remained after 3 cycles	(N. Zhang et al., 2023)
Poplar wood chips	Pyrolysis at 350–650°C	Water washing	78.5% (1st cycle), 58.6% (2nd cycle) regeneration of sulfonamide adsorption	(Guan et al., 2025)

Raw Materials	Modification of Biochar	Regeneration Methods	Adsorption Performance/Regeneration	Ref.
Syagrus coronata endocarp	None	Fenton reaction (Fe^{2+} + H_2O_2)	Max recovery: 19.31% of capacity with Fe^{2+} (1.0 mmol/L) + H_2O_2 (600 mmol/L)	(De Lima et al., 2019)
Enteromorpha prolifera	Acid-activated (HCl + HF)	Thermal regeneration at 200°C	48% (pyrene) and 40% (BaP) of uptake retained after regeneration	(Qiao et al., 2018)
Phosphoric acid-treated biochar	P-GBC (phosphoric acid activation)	H_2O_2 + PMS (peroxymonosulfate)	Up to 94.88% regeneration efficiency; MB max adsorption: 599.66 mg/g	(H. Ding et al., 2023)
Ulva reticulata	Unmodified	Desorption and elution (batch)	Isotherms and kinetics modeled; effective regeneration shown but quantitative capacity not fully disclosed	(Rajagopalan et al., 2022)
Forest/agro-industrial residues	Iron oxide, acid, or nanoscale modifiers	Acid washing, chemical complexation	Adsorption capacities: Ag (1217 mg/g), Pb (560 mg/g), Cu (288 mg/g), Cd (216 mg/g), etc. under optimal conditions	(Gupta et al., 2020)
Wood biochar	General and acid modification	Varies (desorption, chemical, thermal)	50–70% increase in adsorption capacity with modification compared to pristine biochar	(Boraah et al., 2022)

3.3. Mechanisms of Cr(VI) Removal from Wastewater Using Used Biochar

Hexavalent chromium (Cr(VI)) is a highly toxic and mobile contaminant frequently detected in industrial wastewater, where it poses serious threats to both environmental and human health. The urgency to mitigate its impact has spurred the search for effective and affordable remediation technologies. Among them, biochar is a porous, carbonaceous material produced via pyrolysis of biomass that has emerged as a sustainable adsorbent with promising Cr(VI) removal capabilities. Remarkably, even after its initial use, biochar retains physicochemical properties that enable continued effectiveness in removing Cr(VI) through a combination of surface adsorption, ion exchange, and redox mechanisms. This section explores these underlying mechanisms and the factors influencing the continued performance of used biochar in Cr(VI) remediation. Several possible mechanism on Cr(VI) removal using used biochar can be seen in **Figure 2**.

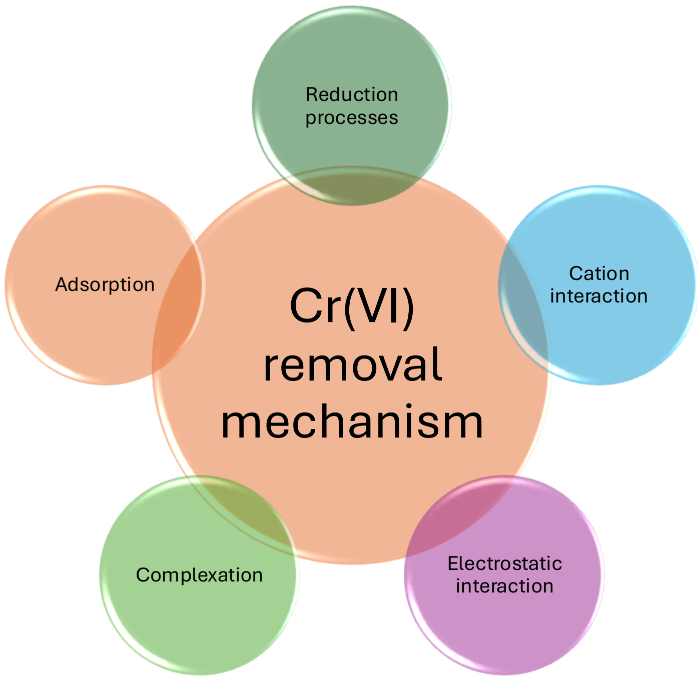

Figure 2. Possible mechanism of biochar in Cr(VI) removal

The effectiveness of biochar in Cr(VI) removal primarily stems from its surface characteristics, including high porosity, extensive surface area, and the abundance of reactive functional groups. These properties facilitate both physical adsorption and chemical interactions with chromium species. Various biochars, produced from feedstocks like walnut shells, corn stalks, and municipal waste, exhibit unique morphologies that affect pore structure and surface functionality, key determinants in their adsorptive efficiency (Alves et al., 2024; Kokab et al., 2021; Yang et al., 2022). Surface adsorption remains the dominant removal mechanism, especially in used biochar, where hydroxyl, carboxyl, and phenolic groups persist and enable continued electrostatic interactions with Cr(VI) anions (Alves et al., 2024).

The efficiency of surface adsorption is significantly influenced by solution pH. Under acidic conditions, Cr(VI) predominantly exists as $HCrO_4^-$, which exhibits strong electrostatic attraction to positively charged sites on the biochar surface (Prathap & Parthasarathy, 2025; Santhosh et al., 2020). These interactions are further supported by ion exchange processes, where Cr(VI) displaces pre-adsorbed ions on biochar's surface, enhancing sorption capacity even in post-use scenarios (Cheng et al., 2023). Used biochar, having already interacted with various ions during initial applications, may possess altered surface chemistry that continues to support ion exchange, particularly when properly regenerated or deployed in slightly modified environmental conditions.

In addition to adsorption and ion exchange, one of the most significant mechanisms contributing to Cr(VI) removal is chemical reduction. Biochar facilitates the reduction of Cr(VI) to the less toxic Cr(III) form through redox reactions involving its electron-donating functional groups. Organic moieties such as phenolics and quinones embedded within the biochar matrix play a pivotal role in donating electrons to Cr(VI), enabling its conversion to Cr(III), which readily precipitates as $Cr(OH)_3$ at neutral to basic pH (A. Li et al., 2020; Samani et al., 2010). This redox process is particularly advantageous in used biochar, where redox-active sites may still be partially intact, and where residual organic material contributes to continued reduction potential.

Studies confirm that biochar exhibits rapid initial adsorption of Cr(VI), with most chromium ions being removed within the first few hours of contact. However, equilibrium conditions may require more time depending on the specific type of biochar and environmental factors such as temperature, concentration, and the presence of competing ions (Asadullah et al., 2019; Sunardi et al., 2023; Yang et al., 2022). The adsorption kinetics of Cr(VI) removal often follow a pseudo-second-order model, indicating that the process is largely governed by chemisorption mechanisms involving valence forces through sharing or exchange of electrons between sorbate and sorbent (A. Li et al., 2020).

Moreover, the performance of used biochar can be further enhanced through chemical or structural modifications. Metal-loaded or chemically activated biochars demonstrate increased selectivity and capacity for Cr(VI) binding. For example, magnesium- and iron-modified biochars exhibit enhanced interaction with chromium due to the introduction of additional active sites and improved electron transfer capabilities (A. Li et al., 2020; Mortazavian et al., 2022; Q. Wang et al., 2023). These modifications can amplify both adsorption and reduction mechanisms, allowing even spent biochar to function effectively in treating chromium-contaminated effluents.

Importantly, functionalization strategies must be chosen with care. Not all modification techniques are universally beneficial, as some may impair the environmental compatibility or stability of biochar (Cheng et al., 2023). For instance, excessive metal loading may introduce secondary pollutants or reduce porosity, diminishing biochar's utility in subsequent applications. Thus, the reusability of biochar hinges not only on its intrinsic properties but also on how it is managed and modified post-use to retain or enhance its reactivity.

Furthermore, feedstock variability plays a role in determining the long-term viability of biochar for Cr(VI) removal. Biochars derived from specific biomass, such as termite-processed material or agricultural residues, may possess superior functional group compositions that support continued Cr(VI) binding even after multiple use cycles (Alves et al., 2024). These properties underline the importance of selecting feedstocks that confer durable adsorptive and redox characteristics, especially for applications involving repeated exposure to heavy metals.

Thus, the removal of Cr(VI) from wastewater using used biochar is governed by a combination of interrelated physicochemical mechanisms—adsorption, ion exchange, and reduction. The unique surface properties and functional groups inherent to biochar facilitate continued effectiveness in post-use scenarios, provided that environmental conditions and modification strategies are appropriately optimized. The integration of kinetic and mechanistic insights with material innovations holds significant promise for scaling the application of reused biochar in wastewater treatment systems. As global concerns about heavy metal pollution intensify, the sustainable use and reuse of biochar for Cr(VI) remediation will remain a critical component of environmental management strategies.

Table 2. Mechanism of Cr(VI) removal using several biochar materials

Raw Materials	Biochar Modification	Performance	Mechanism of Cr(VI) Removal	Ref
Rice husk	Amide-functionalization with 1-[3-(trimethoxysilyl)propyl] urea	97% removal efficiency at pH 2; adsorption capacity of 100 mg/L in 60 minutes	Electrostatic attraction, surface complexation, and reduction of Cr(VI) to Cr(III)	(Ali et al., 2023)
Wheat straw	Ball milling (physical modification)	Adsorption capacity increased to 52.21 mg/g; 100% removal at pH 2, 45°C, 0.1 g dosage in 5 hours	Enhanced surface area leading to electrostatic attraction, redox reactions, and complexation	(Tan et al., 2024)
Sewage sludge-derived biochar	Synthesis of nZVI-BC by liquid-phase reduction method	Cr(VI) adsorption capacity was increased up to 60.32 mg/g, compared to the biochar (39.23 mg/g)	adsorption, reduction of Cr(VI) into Cr(III), then co-precipitation immobilization	(Chen et al., 2022)

Raw Materials	Biochar Modification	Performance	Mechanism of Cr(VI) Removal	Ref
Oak wood biochar	Nearly 100% of Cr(VI) was removed using TP–nZVI–OB at an optimal iron-to-carbon (Fe/C) mass ratio of 2:1	The initial pH had a strong influence on Cr(VI) removal, with 99.9% of Cr(VI) successfully eliminated at an initial pH of 2.0.	The removal mechanism involves adsorption of Cr(VI), its reduction to Cr(III), followed by immobilization through co-precipitation.	(Zhang et al., 2020)
Camphor wood	Unmodified biochar	Significant Cr(VI) removal; specific capacities not specified	Reduction of Cr(VI) to Cr(III) through electrostatic interaction and formation of stable ions	(Xiao et al., 2022)

3.4. Effects of Spent Biochar on Soil Properties

The application of spent biochar, which is biochar that has undergone previous use, typically in pollutant adsorption or agricultural systems, has demonstrated continued effectiveness in enhancing soil health. Its residual physicochemical properties, including porosity, surface functionality, and elemental composition, make it a valuable tool in sustainable soil management. This section explores how spent biochar affects critical soil parameters such as pH, nutrient availability, structure, and microbial activity, with particular attention to its contributions to long-term soil fertility. **Figure 3** presents a conceptual model illustrating the multifaceted role of biochar in influencing soil microbial dynamics, physicochemical soil properties, and greenhouse gas (GHG) emissions within the rhizosphere. The schematic underscores biochar as a potent soil amendment with the potential to improve soil health and contribute to climate change mitigation through its interaction with soil biota and structural attributes.

Biochar's effectiveness stems from its distinctive properties, including a high carbon and aromatic structure, low density, porous architecture, high surface area, alkaline pH, mineral content, and the presence of functional groups (Bolan et al., 2022; Liu et al., 2015; Panwar & Pawar, 2022; Sajjadi et al., 2019). These characteristics collectively enhance several soil physical and chemical parameters. Specifically, biochar reduces soil bulk density, which improves aeration and facilitates root growth (Chang et al., 2021). Its high porosity and surface area lead to increased water retention (water holding capacity), better gas exchange, and enhanced microbial habitats (Adhikari et al., 2022). The alkaline nature of biochar raises soil pH, which can be especially beneficial in acidic soils, thereby improving nutrient availability (Dai et al., 2017). Furthermore, the mineral elements and functional groups present in biochar enhance nutrient supply, increase the soil's cation exchange capacity (CEC), and contribute to the stabilization and accumulation of soil organic carbon (SOC) (Dey et al., 2023; Lorenz & Lal, 2014; Sohi et al., 2010).

In terms of biological interactions, biochar plays a pivotal role in shaping the soil microbial community (Luo et al., 2017). Its porous structure and adsorption capabilities create favorable microhabitats that support microbial colonization and survival (Mukherjee et al., 2022). These changes lead to increased microbial biomass, shifts in microbial community structure, and heightened microbial activity. This, in turn, facilitates enhanced nutrient cycling, organic matter decomposition, and overall soil fertility (Tian et al., 2016). The interactions between biochar and the soil microbiome are crucial for sustaining long-term soil productivity.

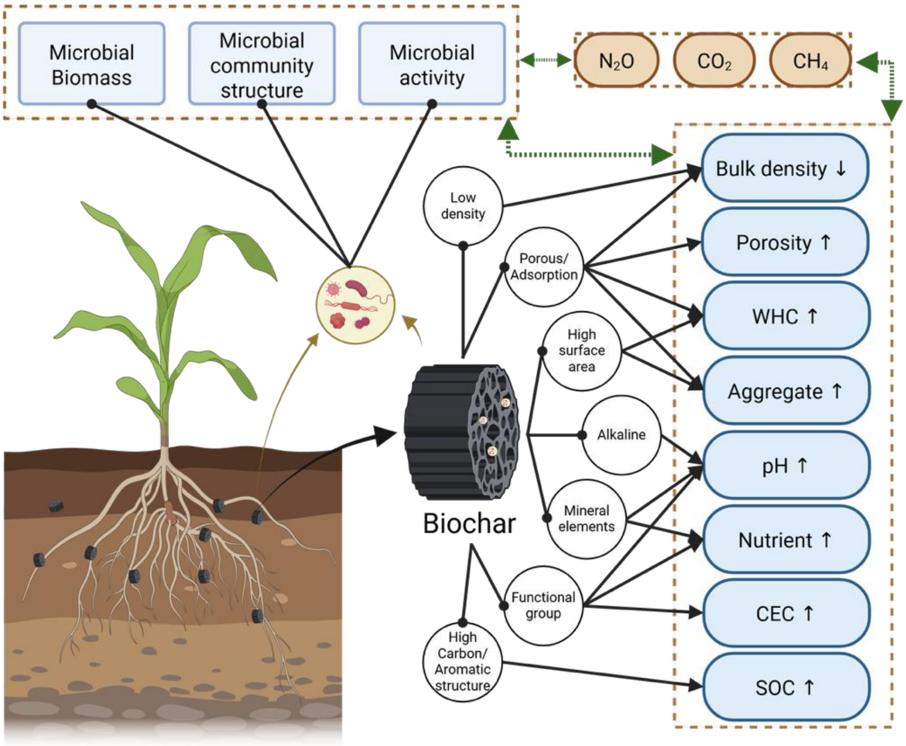

Figure 3. Effect of spent biochar in soil properties

Additionally, Figure 3 also highlights the impact of biochar on greenhouse gas fluxes, particularly nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4). Through its modulation of microbial processes and improvement of soil conditions, biochar can reduce GHG emissions from soils, though outcomes may vary depending on environmental conditions and management practices. The potential for biochar to act as a climate mitigation tool by sequestering carbon and altering microbial-mediated GHG emissions is a significant area of interest in sustainable agriculture.

In other side, one of the most consistent effects of spent biochar is its ability to increase soil pH, especially in acidic soils. The alkaline nature of biochar, retained even after initial application, contributes to its liming effect, neutralizing soil acidity and improving nutrient availability. This shift in pH enhances the soil's cation exchange capacity (CEC), promoting better retention of essential nutrients and reducing the solubility of toxic elements like aluminum (Glaser & Lehr, 2019; H. Wang et al., 2020). The magnitude of this effect depends on the biochar's feedstock and pyrolysis conditions, with biochars made from leguminous materials showing stronger alkalinity due to higher concentrations of basic minerals (J. Yuan & Xu, 2010). Spent biochar, while potentially depleted in some active compounds, typically maintains sufficient alkalinity to exert beneficial effects on soil chemistry over time (Trippe et al., 2015).

Nutrient availability in soils is also positively influenced by spent biochar through its role in nutrient retention, cycling, and slow release. Biochar increases CEC, allowing for improved retention of macronutrients such as nitrogen (N), phosphorus (P), and potassium (K), which are critical for plant growth and productivity (J. Wang et al., 2015). Even after initial use, biochar can continue to act as a reservoir of nutrients, releasing them gradually into the soil solution, thus contributing to sustained fertility (Hossain et al., 2020; Mia et al., 2017). Its porous structure facilitates the adsorption and subsequent slow release of these nutrients, supporting crop needs throughout the growing season. Moreover, spent biochar interacts with soil organic matter and microbial processes, enhancing nutrient cycling and the mobilization of elements like phosphorus for plant uptake (Cordovil et al., 2019).

In addition to chemical improvements, spent biochar contributes to the physical enhancement of soil. Its porous and lightweight structure improves soil aeration, water retention, and aggregation. These changes are particularly valuable in sandy, degraded, or compacted soils, where structural limitations often reduce root penetration and water-holding capacity (Brtnický et al., 2021). Biochar's influence on bulk density and porosity fosters better infiltration rates and reduces surface runoff, which helps conserve water and minimize nutrient loss (H. Wang et al., 2022). The improved soil texture and structure also support root development, enhancing the overall resilience of plants to environmental stresses.

The presence of biochar in soil, even after previous use, creates microhabitats for soil microorganisms, contributing to increased microbial activity and biodiversity. Spent biochar provides stable surfaces and organic substrates that support microbial colonization and metabolic activity. These microbial communities play crucial roles in organic matter decomposition, nutrient mineralization, and soil respiration. Enhanced microbial biomass and activity have been observed in biochar-amended soils, resulting in improved nitrogen cycling and enzymatic functions necessary for maintaining soil fertility (Ducey et al., 2013; Nelissen et al., 2014). Additionally, biochar supports the growth of beneficial rhizosphere organisms, which in turn promote plant health and nutrient uptake (Luan et al., 2023).

However, the effects of spent biochar on microbial processes are not uniformly positive. Its impact can vary based on pyrolysis temperature, feedstock origin, and residual contaminants from prior use. Certain biochars may introduce free radicals or toxic compounds that inhibit microbial communication and function, underscoring the importance of selecting appropriate biochar types for specific soil conditions (Dissanayake et al., 2022; Prendergast-Miller et al., 2013). Despite these challenges, the majority of studies indicate a net positive influence on microbial diversity and activity when biochar is applied at appropriate rates and with consideration of soil characteristics.

Biochar also contributes indirectly to nutrient dynamics through its effects on enzymatic activities associated with microbial processes. The stimulation of soil enzymes linked to nitrogen transformation and organic matter decomposition suggests that biochar creates a more biologically active environment, even after multiple use cycles. This microbial enhancement supports a more efficient nutrient cycle, thereby improving soil fertility and plant productivity (Biederman & Harpole, 2012).

The structural and chemical stability of biochar makes it a durable soil amendment. Unlike synthetic fertilizers or organic composts that decompose quickly, biochar persists in soil for years, continuously contributing to soil quality through physical improvement and nutrient retention (Berek et al., 2018). Its long-term integration into agricultural systems offers a sustainable approach to soil restoration, particularly in regions facing degradation due to intensive cultivation, nutrient mining, or climate-induced stress.

Table 3. Effect of spent biochar in soil propoertis

Soil Property	Observed Effect	Result	Ref.
Soil pH	Increased pH due to the alkaline nature of biochar, aiding in the amelioration of acidic soils.	Biochar application increased soil pH by 1.0 to 1.4 units in acidic soils.	(Hui, 2021)
Cation Exchange Capacity (CEC)	Enhanced CEC, improving nutrient retention and availability.	CEC increased by 20% following biochar application.	(H. Singh et al., 2022)
Soil Organic Carbon (SOC)	Elevated SOC levels, contributing to improved soil fertility and carbon sequestration.	SOC content increased by 27% with biochar amendment.	(Calcan et al., 2022)
Bulk Density	Reduction in bulk density, enhancing soil aeration and root penetration.	Bulk density decreased by approximately 50% in treated soils.	(Calcan et al., 2022)

Soil Property	Observed Effect	Result	Ref.
Water Holding Capacity (WHC)	Improved WHC, aiding in better water retention and availability to plants.	WHC increased by 5.9% to 25.5% depending on soil type and biochar characteristics.	(Hui, 2021)
Soil Porosity	Enhanced porosity, facilitating improved air and water movement within the soil profile.	Total pore volume increased by 16% post biochar application.	(Hui, 2021)
Nutrient Availability	Increased availability of essential nutrients such as nitrogen and phosphorus, promoting plant growth.	Not specified quantitatively; however, studies report enhanced nutrient availability with biochar use.	(Kabir et al., 2023b)
Soil Microbial Activity	Stimulated microbial biomass and enzymatic activities, leading to improved soil health and nutrient cycling.	Not specified quantitatively; however, biochar application has been associated with increased microbial activity.	(Kabir et al., 2023b)
Soil Structure and Aggregation	Improved soil structure and aggregate stability, reducing erosion and enhancing root development.	Soil loss reduced by 50% and 60% with biochar application rates of 2.5% and 5% w/w, respectively.	(Premalatha, Poorna Bindu, et al., 2023)
Greenhouse Gas Emissions	Reduction in emissions of greenhouse gases such as N_2O, contributing to climate change mitigation.	N_2O emissions decreased by up to 71% with biochar application.	(Lyu et al., 2022)

Thus, spent biochar continues to serve as an effective amendment for enhancing soil pH, increasing nutrient availability, improving soil structure, and stimulating microbial activity. While its functionality may be somewhat reduced compared to freshly produced biochar, its enduring physical and chemical properties enable it to contribute meaningfully to soil health and productivity. These benefits position spent biochar as a critical component in circular agricultural systems aimed at maintaining fertility, promoting sustainability, and improving environmental outcomes in diverse agroecosystems.

3.5. Circular Economy Approach in Biochar Reuse

The circular economy (CE) paradigm emphasizes the optimization of resource use, minimization of waste, and the continual circulation of materials within economic and ecological systems. In this context, the reuse of biochar presents a compelling case for the integration of circularity into both agricultural and industrial domains. Biochar, produced through the pyrolysis of organic biomass, embodies the principles of waste valorization and sustainability by transforming organic residues into a versatile product with multiple life-cycle applications. This section explores how the reuse of biochar supports circular economy strategies, with particular emphasis on resource efficiency, waste minimization, and systemic sustainability.

Within agricultural systems, biochar reuse exemplifies circularity by closing the loop between biomass waste generation and soil fertility management. Agricultural residues such as crop prunings, spent mushroom substrates, and forestry waste, which would otherwise be discarded or incinerated, are repurposed into biochar, thereby reducing waste and generating a value-added product (Aiduang et al., 2025; Jindo et al., 2020). Once applied to soil, biochar enhances soil structure, improves pH balance, and increases nutrient availability, contributing directly to improved crop yields and reduced dependency on synthetic fertilizers (Kabir et al., 2023a; Kaur et al., 2024a). Even after initial use, spent biochar retains enough functional properties to be reused, further extending its lifecycle and aligning with the CE objective of maximizing resource utility.

Beyond agronomic benefits, biochar plays a critical role in carbon management. The stable carbon structure of biochar allows it to function as a long-term carbon sink, sequestering atmospheric CO_2 and storing it in soil ecosystems for extended periods. This function supports decarbonization efforts within agricultural landscapes and contributes to global climate change mitigation goals (Enaime et al., 2023; Sadowska et al., 2020). The reuse of biochar sustains this carbon sequestration function over multiple application cycles, reinforcing its value as a climate-resilient strategy embedded within a circular resource framework (Prochnow et al., 2024; Shanmugaraj et al., 2024).

Resource recovery is another critical dimension of biochar reuse within circular economy models. By converting organic waste materials into biochar, producers are able to capture and repurpose nutrients and carbon that would otherwise be lost. This transformation diverts biomass from landfills and open burning, reducing environmental pollution and generating a soil amendment that supports nutrient cycling and productivity (Aiduang et al., 2025; Neve et al., 2023). Moreover, biochar derived from specific sources such as spent mushroom substrate or vetiver roots has demonstrated potential for enhancing soil fertility while simultaneously addressing waste management challenges in food and agricultural industries.

In industrial settings, biochar's role in promoting circularity extends into the production of sustainable materials and environmental protection technologies. Biochar has been successfully incorporated into construction materials, such as cement and concrete, where it improves mechanical performance and reduces the carbon footprint of production processes (Commeh et al., 2024; Diaz et al., 2020). These applications exemplify circular material innovation by utilizing what would otherwise be considered waste as functional industrial inputs, contributing to resource efficiency across sectors. Furthermore, biochar-starch composites have been developed for biodegradable packaging and containers, demonstrating its utility in green manufacturing and consumer product design (Diaz et al., 2020).

Biochar's capacity as an adsorbent further supports industrial circularity through its application in environmental remediation. In wastewater treatment systems, reused biochar has been applied to remove organic pollutants and heavy metals, highlighting its role as a multifunctional material capable of contributing to both waste valorization and pollution control (Mayilswamy et al., 2023). This dual functionality, pollutant capture and material reuse, epitomizes circular economy thinking by delivering environmental benefits while reducing the demand for virgin remediation materials.

Despite its potential, the widespread adoption of biochar reuse within circular systems faces several challenges. Key among these are issues related to the standardization of production methods, variability in feedstock quality, and inconsistency in biochar properties. These factors can impact both the agronomic and industrial performance of reused biochar, thereby limiting its scalability (Kabir et al., 2023a; Nair et al., 2017). Furthermore, logistical barriers such as transportation costs, lack of regulatory clarity, and limited market incentives hinder broader integration of biochar into CE-aligned practices.

Addressing these challenges requires coordinated efforts across research, policy, and market development. Establishing quality standards for biochar production and application is essential to ensuring product consistency and user confidence (Enaime et al., 2023). Educational initiatives and technical training can also help increase awareness and understanding of biochar's role in sustainability frameworks. In parallel, policy instruments that incentivize the use of circular materials in agriculture and industry, such as subsidies, carbon credits, or waste reduction mandates, could accelerate the transition toward a biochar-integrated circular economy.

The reuse of biochar serves as a practical and scalable pathway for advancing circular economy principles in both agricultural and industrial contexts. By transforming organic waste into a multifunctional product, biochar exemplifies resource efficiency, waste minimization, and climate resilience. Its applications from soil enhancement and carbon sequestration to green construction and wastewater treatment, illustrate the broad systemic value of this material. As the global demand for sustainable resource management intensifies, integrating reused biochar into circular frameworks offers a promising avenue for ecological and economic sustainability.

3.6. Case Studies and Practical Implementations

The real-world implementation of biochar technologies has expanded beyond laboratory research into field trials and pilot-scale applications, demonstrating the material's potential for sustainable development. Biochar's dual utility in wastewater treatment and soil enhancement illustrates its value across multiple environmental and industrial sectors. This section synthesizes case studies and practical implementations to showcase how reused biochar performs effectively in real scenarios, contributing to resource recovery, pollution reduction, and soil regeneration.

In the realm of wastewater treatment, several case studies highlight biochar's role in removing contaminants and supporting water reuse. A constructed wetland study using reed plants in combination with biochar demonstrated effective removal of heavy metals such as cadmium, copper, and manganese from wastewater (Asaad et al., 2022). The filtration capability of biochar contributed significantly to pollutant reduction through surface adsorption and ion complexation, offering a sustainable strategy for decentralized water reclamation. In another example, diatom biochar was used to recover gold ions (Au(III)) from both synthetic and real electroplating wastewater, showing high adsorption efficiency and potential for resource recovery in industrial effluent management (L. Wang et al., 2023).

Innovative applications of engineered biochar also show promise. Magnetic biochar produced from sewage sludge was tested for lead (Pb) removal in a pilot-scale study. This biochar type demonstrated high adsorption capacity and reusability, enhancing the performance of wastewater treatment systems while promoting the valorization of sewage waste (Ifthikar et al., 2017). Similarly, modified biochar using graphene oxide showed improved sorption of organic micropollutants in industrial wastewater, illustrating how functional enhancements can increase the environmental value of reused biochar (Regkouzas et al., 2023).

In agricultural contexts, practical implementations of biochar have proven effective in improving soil quality and crop productivity, especially in contaminated or nutrient-deficient soils. A study involving sunflower cultivation on wastewater-irrigated soil showed that biochar significantly mitigated cadmium toxicity and enhanced nutrient availability, including nitrogen, phosphorus, and potassium (Bashir et al., 2021). The reused biochar played a role in desorbing cations and increasing organic carbon, supporting plant health under stress conditions. Similarly, in urban agriculture systems, biochar applied alongside wastewater irrigation improved crop yields and increased soil organic carbon content, highlighting its dual benefit in filtering wastewater and enriching soils (Asirifi et al., 2023).

Biochar's ability to remediate polluted soils is further demonstrated in a study on cadmium- and lead-contaminated agricultural land. When applied to soil cultivated with corn, biochar not only stabilized the heavy metals but also enhanced plant biomass, reducing the bioavailability of contaminants and promoting safe food production (Shirzad et al., 2024). This stabilization function positions biochar as a remediation tool that can be safely reused in moderately contaminated agricultural zones.

Nutrient recovery is another area where biochar shows practical promise. In a study focused on swine wastewater, magnesium-modified corn biochar was used to capture phosphorus from liquid waste streams (Fang et al., 2014). The recovered phosphorus-enriched biochar was found to be suitable for reuse as a slow-release fertilizer, closing the loop between waste treatment and nutrient delivery in agriculture. A similar approach was adopted in another study that explored phosphorus recovery from municipal wastewater, where the treated biochar was successfully repurposed as a fertilizer, aligning with circular economy goals (Yao et al., 2013).

Pilot-scale and industrial implementations further reinforce the viability of biochar reuse. In an agricultural study involving biochar from various biomass feedstocks, applications led to improved soil structure, increased nutrient retention, and enhanced water-holding capacity, all crucial attributes for climate-resilient farming (Jindo et al., 2020). Scaling efforts were also observed in the production of biochar from olive tree prunings, where the material demonstrated no phytotoxicity and improved soil fertility in large-scale trials (Crespo-Barreiro et al., 2023). These outcomes indicate that biochar systems can transition from experimental to commercial scales with measurable environmental benefits.

In industrial applications, reused biochar has been integrated into construction materials to reduce carbon emissions and improve material properties. One study reported that rice straw biochar, when blended with cement, enhanced both compressive strength and thermal conductivity, providing a sustainable alternative to conventional construction components (D. Zhang et al., 2022). This use case reflects how industrial sectors can incorporate biochar into circular material flows, supporting both performance and emissions reduction.

Additionally, biochar has been evaluated for its role in carbon sequestration. In an analysis of biochar produced via fast and slow pyrolysis, researchers found that the material not only improved soil fertility but also offered significant potential for long-term carbon storage (Brown et al., 2010). The study linked biochar application with reduced greenhouse gas emissions and better nutrient use efficiency, reinforcing its dual value in climate mitigation and soil management.

Collectively, these case studies underscore the real-world potential of reused biochar across sectors. From mitigating heavy metal pollution in wastewater to enhancing agricultural productivity and sequestering carbon, biochar applications have moved beyond theoretical models into validated, scalable solutions. While variability in feedstocks and production methods remains a challenge, these implementations highlight a growing consensus on biochar's role in sustainable development. Integrating biochar reuse into environmental policy and industrial practice represents a practical and impactful step toward advancing circular economy objectives.

3.7. Limitations, Risks, and Research Gaps

Despite the growing interest in biochar reuse for environmental remediation and agricultural enhancement, several limitations and uncertainties remain that challenge its broader implementation. As biochar transitions from a laboratory-scale solution to a practical, field-deployable technology, concerns regarding environmental safety, cost-effectiveness, regulatory oversight, and performance stability must be critically addressed. Understanding these limitations is essential for refining biochar applications and advancing its integration into sustainable development strategies.

One of the most prominent concerns is the risk of contaminant leaching from reused or spent biochar. After biochar has been used to adsorb pollutants such as heavy metals or organic contaminants, there is a potential for these substances to be released back into the environment under certain conditions. Changes in soil pH, moisture content, and redox potential can destabilize adsorbed compounds, particularly in acidic or saline environments, leading to re-mobilization of toxicants (Rahim et al., 2022). The risk of leaching not only undermines the environmental benefits of biochar but also introduces potential hazards to human health and soil ecosystems, especially if biochar is reused in agricultural settings without adequate pre-treatment or risk assessment.

The economic feasibility of biochar reuse presents another critical limitation. The costs associated with biochar production, transportation, modification, and post-use treatment can be prohibitively high for large-scale deployment, particularly in low-income or resource-constrained regions. While feedstock availability and pyrolysis efficiency play a significant role in determining production costs, additional expenses incurred from engineering biochar for specific applications, such as metal modification or surface activation, can reduce its competitiveness compared to conventional remediation materials or soil amendments. Furthermore, logistical barriers related to distribution and storage add to the complexity of adopting biochar as a scalable solution.

Regulatory and standardization challenges also hinder the mainstream adoption of biochar reuse. Currently, there is a lack of internationally harmonized guidelines for biochar classification, quality control, and application limits in various environmental settings. Inconsistent regulatory frameworks across countries create ambiguity regarding the acceptable levels of contaminants, stability requirements, and reuse protocols for spent biochar. This absence of clear standards limits the confidence of stakeholders, including farmers, industry leaders, and policymakers, in investing in biochar technologies. Moreover, the lack of legal definitions for reused or post-treatment biochar products complicates their categorization within existing waste or resource management systems.

Performance degradation is another area of concern. Over time, biochar's physical and chemical properties may deteriorate, particularly after exposure to environmental stressors or after repeated use in adsorption cycles. Reduced surface area, pore clogging, and the loss of functional groups can significantly diminish its adsorption capacity and soil amendment benefits. While some regeneration techniques exist, such as thermal treatment or chemical washing, these processes are often energy-intensive and may not restore biochar to its original performance levels. Consequently, understanding the lifespan and degradation pathways of biochar in different environments is essential for predicting its long-term effectiveness.

In addition to these limitations, several research gaps persist that need urgent attention. There is a pressing need for long-term field studies that evaluate the environmental behavior and performance of reused biochar under variable climatic, soil, and contamination conditions. Most current data are derived from short-term laboratory experiments, which may not accurately capture the complexities of real-world systems. Further, the interactions between biochar and native soil microbial communities over multiple cropping seasons remain poorly understood, especially in relation to nutrient cycling and plant health outcomes.

Another underexplored area involves the development of safe and efficient biochar regeneration methods that retain or enhance its functional properties while minimizing environmental risks. Research should also focus on assessing the cumulative ecological impacts of large-scale biochar applications, including potential trade-offs between pollution mitigation, carbon sequestration, and biodiversity.

In summary, while the reuse of biochar holds substantial promise for sustainable wastewater treatment and soil enhancement, its widespread adoption is limited by concerns over contaminant leaching, economic barriers, regulatory ambiguity, and performance decline. Addressing these challenges through targeted research, improved policy frameworks, and stakeholder collaboration will be crucial to unlocking the full potential of biochar within circular and regenerative systems.

3.8. Policy Recommendation

To facilitate the widespread and sustainable implementation of reused biochar in environmental remediation and agricultural systems, a comprehensive and coherent policy framework is essential. Figure 4 showed the policy and strategy recommendation for utilization biochar for removal Cr(VI). A primary recommendation is the development of standardized regulations for the production, characterization, and classification of both fresh and spent biochar. These regulations should establish clear thresholds for contaminants, define minimum physicochemical property requirements, and provide detailed guidelines for safe reuse (W. Wang et al., 2023c). Implementing a formal certification system for biochar products would further promote market confidence and ensure regulatory compliance (Cowie et al., 2012; Jan Veres et al., 2014).

Economic policy instruments are also crucial for supporting the adoption of reused biochar. Governments should introduce financial incentives such as tax reductions, carbon credit schemes, and direct subsidies aimed at offsetting the costs associated with biochar production, transportation, and regeneration (Casey et al., 1999). These measures would help enhance the economic viability of biochar in comparison to conventional alternatives, while simultaneously advancing environmental objectives such as pollution reduction and carbon sequestration.

Moreover, it is important that biochar reuse be explicitly integrated into national sustainability frameworks. Policymakers should recognize biochar as a valuable tool for achieving several Sustainable Development Goals, including clean water and sanitation (SDG 6), responsible consumption and production (SDG 12), and climate action (SDG 13) (Azzi et al., 2021; Cordeiro & Sindhøj, 2024). Incorporating biochar into national and subnational policies will promote policy coherence and encourage broader institutional support.

Investment in research and development is another key area requiring attention. Future research should prioritize the advancement of regeneration methods that are cost-effective, energy-efficient, and environmentally safe. In particular, the development of biological and low-temperature chemical regeneration techniques should be supported (Ghosh et al., 2023; Kaur et al., 2024b). Furthermore, long-term field studies are needed to evaluate the performance and ecologic al interactions of reused biochar under diverse environmental conditions (H. Li et al., 2022).

Equally important is the need for education and capacity-building initiatives targeted at end-users. Training programs should be designed for farmers, environmental practitioners, and industrial stakeholders to promote awareness of biochar benefits, application methods, and safety precautions. Demonstration projects and participatory extension models can enhance practical understanding and foster local engagement in biochar reuse strategies.

To support large-scale implementation, infrastructure development and market access must also be addressed. Policymakers should facilitate the establishment of regional biochar production and processing centers, particularly in areas with significant biomass availability (Gwenzi et al., 2015). Strengthening the supply chain and promoting market linkages between producers and users will enhance the scalability and sustainability of biochar reuse systems.

Finally, it is essential to implement robust monitoring and evaluation frameworks. These should include standardized metrics for assessing the environmental and socio-economic impacts of biochar reuse, such as soil health indicators, pollutant retention capacity, greenhouse gas emissions, and crop productivity (Awogbemi & Kallon, 2023). Transparent reporting and periodic assessments will support adaptive management and continuous improvement of biochar-based interventions.

Figure 4. Policy recommendation for biochar utilization for Cr(VI) removal

3.9. Future Directions and Recommendations

The reuse of spent biochar presents a promising pathway toward achieving sustainable environmental management and resource circularity. However, to fully harness its potential, coordinated efforts among researchers, practitioners, and policymakers are needed to overcome current limitations, standardize applications, and develop innovative strategies that support large-scale deployment. Future research and implementation strategies should focus on optimizing biochar reuse, enhancing its multifunctionality, and integrating it into broader environmental and agricultural frameworks.

For researchers, a key priority is the development of long-term field studies that evaluate the environmental fate and performance of reused biochar under diverse soil, climate, and land-use conditions. Current data predominantly arise from short-term laboratory experiments, which fail to capture complex field dynamics such as soil-microbe-plant interactions, seasonal variability, and cumulative environmental effects. Longitudinal studies should focus on the retention of biochar's physical integrity and functional properties over time, especially when exposed to repeated use or contaminant loading. Additionally, investigating how spent biochar interacts with different types of contaminants, both inorganic and organic will provide deeper insights into its versatility and constraints in real-world applications.

The optimization of biochar regeneration methods represents another critical area of advancement. Research efforts should explore low-energy, cost-effective techniques for rejuvenating spent biochar without compromising its structural integrity or creating secondary environmental burdens. Approaches such as mild chemical washing, microbial reactivation, or integration with composting processes may offer scalable solutions to extend biochar’s functional lifespan. Moreover, the development of hybrid materials, such as combining biochar with nanomaterials or metal oxides, could enhance its reusability while targeting specific pollutants or soil deficiencies.

From a practical standpoint, practitioners and land managers should focus on integrating reused biochar into existing agricultural and wastewater treatment systems through modular and adaptable strategies. Demonstration projects in different agroecological zones would provide valuable insights into the feasibility, cost-effectiveness, and user acceptance of spent biochar technologies. These projects should prioritize participatory approaches, involving local farmers and stakeholders in biochar application, monitoring, and evaluation. Knowledge transfer and capacity-building initiatives will be essential to ensure that end-users understand the benefits, limitations, and best practices for biochar reuse in their specific contexts.

In parallel, robust policy and regulatory frameworks are essential to support the safe and effective reuse of biochar. Policymakers should work toward developing clear classification standards for spent biochar, distinguishing it from waste or hazardous materials while promoting its recognition as a valuable resource. Establishing quality control protocols for feedstock selection, pyrolysis conditions, and contaminant thresholds will help build confidence among users and investors. Furthermore, incentivizing sustainable practices through subsidies, carbon credits, or inclusion in green certification programs can accelerate the adoption of biochar technologies across agricultural and industrial sectors.

To promote large-scale deployment, investment in biochar infrastructure and supply chains must be expanded. Regional biochar production hubs, linked to agricultural cooperatives, waste management facilities, or industrial partners, can create synergies that reduce costs and improve access. Collaborative networks involving universities, private sector actors, and community organizations should be encouraged to foster innovation and share knowledge across disciplines and regions.

Lastly, future strategies must consider the broader ecological and socio-economic impacts of biochar reuse. Integrated life cycle assessments and cost-benefit analyses should be conducted to evaluate the trade-offs and long-term sustainability of biochar systems. These evaluations should include not only agronomic and environmental outcomes but also social dimensions such as labor requirements, gender equity, and community resilience. Aligning biochar strategies with national and global sustainability goals, such as the UN Sustainable Development Goals (SDGs), will ensure that their implementation contributes to inclusive and regenerative development pathways.

4. Conclusions

The sustainable reuse of biochar offers a transformative opportunity to address pressing environmental challenges related to wastewater treatment, soil degradation, and resource inefficiency. As a product derived from the pyrolysis of organic biomass, biochar possesses unique physicochemical properties—such as high porosity, surface reactivity, and nutrient retention capacity—that enable its application across agricultural and industrial sectors. This review has highlighted the growing body of evidence supporting biochar's role in pollutant adsorption, soil fertility enhancement, and circular economy integration.

Through mechanisms such as surface adsorption, ion exchange, and redox reactions, spent biochar remains functionally active for the removal of hazardous substances, particularly hexavalent chromium from wastewater. Simultaneously, its residual benefits in soil systems, including pH stabilization, nutrient availability, improved structure, and stimulation of microbial activity, underscore its continued value even after initial application. Case studies from diverse geographical and operational contexts have demonstrated the real-world applicability of reused biochar in treating contaminated water, rehabilitating polluted soils, and improving crop productivity, often with measurable ecological and economic gains.

Despite these promising outcomes, challenges persist. Concerns related to contaminant leaching, performance degradation, economic barriers, and regulatory uncertainties must be addressed through targeted research and policy development. Furthermore, the absence of standardized guidelines for biochar reuse complicates its integration into existing environmental and agricultural management systems.

Looking forward, advancing the sustainable reuse of biochar will require coordinated actions across multiple fronts. Researchers must prioritize long-term field evaluations and regeneration technologies; practitioners should promote scalable, site-specific applications; and policymakers must develop supportive frameworks that recognize biochar as a renewable and valuable resource. Integrating biochar reuse into broader sustainability and circular economy agendas can help close nutrient loops, reduce environmental pollution, and enhance climate resilience.

Thus, reused biochar represents not only a low-cost, eco-efficient tool for pollution control and soil restoration but also a strategic material that aligns with global efforts toward sustainable development. With continued innovation and collaborative governance, the widespread application of spent biochar can become a cornerstone of environmentally sound and economically viable resource management practices.

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