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Assessment of Biochar-Amended Urban Soils for Enhanced Stormwater Retention and Heavy Metal Mitigation

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Abstract
Urbanization has intensified challenges associated with stormwater management and soil contamination, creating a need for sustainable remediation strategies. This research evaluates the effectiveness of biochar-amended urban soils in improving stormwater retention and reducing heavy metal mobility. Field-scale experimental plots were established in a densely developed urban environment and treated with varying biochar concentrations derived from agricultural biomass residues. Soil hydraulic properties, infiltration rates, water-holding capacity, and concentrations of selected heavy metals were monitored over an extended observation period. Comparative analyses revealed that biochar incorporation significantly increased water retention and enhanced infiltration performance, thereby reducing surface runoff risks during intense rainfall events. Additionally, treated soils exhibited lower mobility of lead, cadmium, and zinc due to enhanced adsorption mechanisms and improved soil structure. Statistical assessment confirmed a positive correlation between biochar application rates and environmental performance indicators. The study demonstrates that biochar can function simultaneously as a stormwater management amendment and a soil remediation material. These findings support the integration of biochar-based approaches into sustainable urban infrastructure planning and environmental restoration initiatives aimed at improving resilience and ecological quality.
Keywords: ***Biochar, Urban Soils, Stormwater Management, Heavy Metal Remediation, Sustainable Infrastructure, Soil Amendment, Environmental Engineering, Water Retention.***

1.Introduction

1.1 Water Management and Soil Degradation Issues in Urban Storm Water

The natural water cycle in urban areas has significantly been altered by rapid urban growth. Building impervious surfaces like roads, parking lots, and structures have a negative impact on the amount of rainwater that is allowed to percolate into the ground naturally. This causes a significant amount of storm water to run off the land and carry sediments, nutrients, heavy metals, oils and other contaminants to the nearby rivers, lakes and drainage systems. Heavy rain may lead to the overloading of urban drainage systems, which may trigger flooding and water pollution. Human activities also heavily impact urban soils. Soil compaction, which decreases the amount of pore space in the soil, often occurs during construction, traffic, excavation and land grading and can hinder infiltration of water into the soil. Compacted soils are less water-holding, have poor aeration and limited rooting capacity. During development in many cities, topsoils are removed or disturbed, which leads to soils with low organic matter content and little biological activity. The impact of these conditions makes it harder for the soil to absorb and filter stormwater effectively.

Urban water management systems are under even greater strain due to the effects of climate change. There has been an increase in frequency and intensity of rainfall in many places, leading to increases in runoff and putting further strain on urban drainage systems. Meanwhile, extended dry spells may cause soils to deteriorate and vegetation to suffer. Soil structure and storm water management practices that are sustainable and beneficial are becoming more important in urban settings(1).

1.2 Biochar as a Sustainable Urban Soil Amendment

Biochar has become a popular and sustainable soil amendment choice for cities. It is a substance rich in carbon that is created by burning biomass under low conditions of oxygen. Typical feedstocks for biochar production include agricultural residues like rice husks, corn stalks, wheat straw, sugarcane bagasse, and other agricultural residues. The production of biochar from these residues not only provides value for crop residues, but also helps to minimise open burning in fields and emissions.

Biochar is especially useful for enhancing degraded urban soils due to its physical and chemical properties. It has a very porous structure which promotes soil porosity and water holding capacity to retain water in times of rainfall.

Better soil structure can also enhance infiltration rates and allow stormwater to move more efficiently into the soil profile, thus decreasing surface runoff. The properties are particularly useful in compacted urban soils where natural infiltration is often restricted.

Biochar can also enhance soil fertility. The ability of biochar to hold onto nutrients, including nitrogen, phosphorous and potassium, which has a large surface area and high adsorption capacity, minimizes loss of nutrients through leaching. Furthermore, biochar can also enhance the CEC and help to create a more stable soil environment for microorganisms. Better soil microbial activity promotes nutrient cycling and soil health, which is better for plants.

Biochar also has the ability to trap and hold different types of contaminants. Studies have indicated that biochar is able to bind heavy metals, hydrocarbons and other pollutants often associated with urban runoff. It can enhance the quality of the infiltrated water and minimize the transport of contaminants to groundwater and receiving water bodies as a pollutant retention function. Due to these multifaceted advantages, biochar is now being integrated into green infrastructure applications like bioretention cells, rain gardens, bioswales and urban planting sites.

Biochar has further benefits from a sustainability point of view because of its ability to store carbon for extended periods of time. Pyrolysis trapping of carbon results in a high portion of stabilized carbon in soil that can last for decades or even centuries. This helps to sequester carbon and to enhance soil function. Biochar can be a viable alternative for sustainable urban soil management and stormwater control in the context of environmental quality and climate resilience of cities(2).

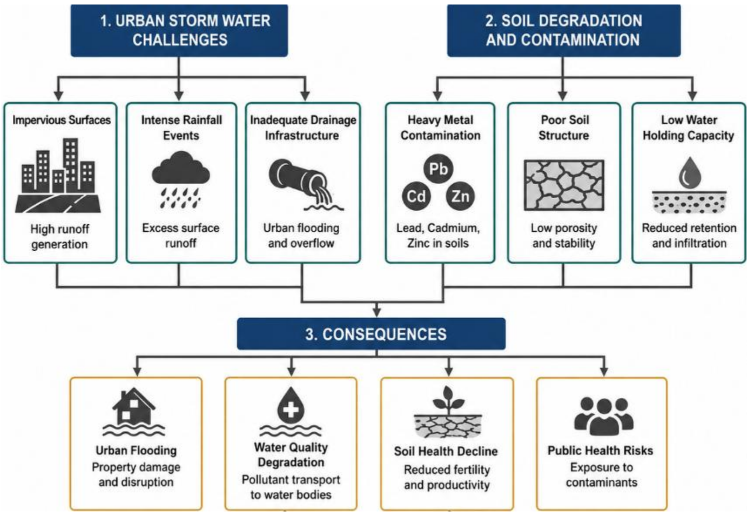


DIAGRAM 1 Urban stormwater and soil degradation flowchart

1.3 Research Objectives and Scope

- To test the application of agricultural biomass derived biochar for enhancing the soil properties in cities.
- To investigate how biochar application affects infiltration and reduction of stormwater runoff.
- To investigate the effect of soil biochar amendment on soil water retention.
- Assess the nutrient holding ability of biochar enhanced soils and the ability to mitigate transport of pollutants.
- To compare performance indicators of the environment between amended and non-amended plot.
- To offer guidelines for practical application of biochar in urban stormwater management and soil restoration applications.

2.Urban Soil Conditions and Biochar Amendment Design

2.1 Characteristics of the Urban Field Site

The location of the study site was in an urbanized community with a high percentage of impervious surfaces and mixed land use. The roads, walkways, parking areas and landscape green spaces surrounding the infrastructure were altered and contributed to altered hydrological conditions. Stormwater containing runoff from nearby paved surfaces was directed to the study site during the rain events, which makes it ideal for studying soil-water interactions under urban conditions.

The preliminary soil study showed typical urban soil degradation characteristics. The soils were moderately to highly compacted from previous construction and continued human disturbance. The reduction in pore space reduced infiltration and increased the surface ponding potential after rainfall. The relatively low levels of organic matter were caused by the degradation of the natural top soil and a decrease in the amount of organic matter applied over time.

There was also moisture distribution variation and vegetation cover on the site. Poor drainage conditions caused localized flooding in the wet areas, while inadequate water holding capacity resulted in swift drying over other areas. These conditions gave us the right opportunity to test if the application of biochar amendment can enhance soil structure, water holding capacity and storm water management(3).

2.2 Agro-wastes provide abundant supply of biochar.

Step 1: Feedstock Selection

Farm waste like rice husks, corn stalks, wheat straw, or sugarcane bagasse were chosen because they are easily accessible, inexpensive, and suitable for making biochar.

Step 1: Materials and prepare your materials.

The biomass materials were harvested and cleaned then air-dried to minimize water content prior to processing.

Step 3: Size Reduction

The biomass was chopped or shredded into smaller pieces in order to have a more uniform heating during pyrolysis process.

Step 4: Pyrolysis Process

Biochar was produced by the prepared biomass under high temperature (400°C to 600°C) conditions in a low oxygen environment.

Step 5: Cooling and Recovery

The pyrolysis plant was used to pyrolyse the biochar, after which it was cooled under controlled conditions to prevent combustion and maintain the carbon rich structure of the biochar.

Step 6: Crushing and Sieving

The biochar was crushed and sieved to create the same particle size for application to soil.

Step 7: Quality Assessment

Various basic properties, including pH, moisture content, bulk density and porosity were measured to ensure suitability of the biochar for agricultural uses.

TABLE 1 Summary of Urban Soil Conditions, Biochar Preparation, and Environmental Assessment

Component	Description	Purpose
Urban Soil Conditions	Compacted soils with low organic matter, variable moisture distribution, poor infiltration, and increased runoff potential.	Establish baseline conditions for evaluating biochar effectiveness.
Biochar Production and Application	Biochar produced from agro-wastes (rice husks, corn stalks, wheat straw, sugarcane bagasse) through pyrolysis (400–600°C), followed by crushing, sieving, and soil incorporation at different application rates.	Improve soil structure, porosity, water retention, and stormwater management performance.
Environmental Performance Indicators	Infiltration rate, runoff volume, soil moisture retention, pollutant retention, bulk density, porosity, organic carbon, and vegetation response.	Assess the environmental benefits of biochar amendment in degraded urban soils.

2.3 Biochar rates of application and plot setup

Experimental plots were set up to rate the performance of biochar amended soil with control soils. The plots were all designed so that they had similar dimensions, slope and exposure to rainfall so that similar comparisons of results could be made. Replicated plots were used to minimise the variability and increase reliability of the results. Biochar was added to the top layer of soil prior to beginning of monitoring period. To assess the effect of different amounts of biochar on soil and hydrological performance, different application rates were chosen. A control treatment without biochar was used as a standard and the three different application rates were used to determine the optimum application rate of the amendment.

Biochar was well mixed in the soil to ensure even distribution across each of the treatment plots. After application, the plots were left to stabilize prior to the start of data collection. Activities were monitored under natural rainfall conditions and supplemented with artificial watering if required. This design allowed the evaluation of infiltration, runoff generation, soil moisture changes, and pollutant retention under realistic urban conditions.

2.4 Environmental Performance Indicators

Several environmental indicators were used to assess the effectiveness of biochar amendment. An infiltration rate was used as a primary indicator as it directly relates to the soil's capacity to absorb the rain and reduce surface runoff. The higher the infiltration rates, the better the hydraulic performance and the lower the risk of urban flooding.

Volumes of runoff were also observed to assess the effectiveness of biochar in decreasing runoff volume from plots during rainfall events. The water holding capacity of the soil was determined by measuring soil moisture regularly to evaluate changes. The retention of moisture will be useful for vegetation growth and will help keep the soil functioning in times of drought(4).

Pollutant retention was assessed by the inclusion of water quality indicators. Nutrient concentrations, suspended solids and selected contaminants typically associated with urban runoff were measured. Less movement of pollutants in the soil profile suggests better filtration and adsorption.

Other parameters were soil bulk density, soil porosity, organic carbon and vegetation response. All these parameters were used together to assess the effect of biochar on soil quality and stormwater management. These indicators were analysed together to draw conclusions about the environmental advantages of biochar as a sustainable soil amendment for urban degraded soils.

3.Hydrological Response of Biochar-Amended Soils

3.1 Soil Hydraulic Property Assessment

Soil hydraulic properties are important in the movement, infiltration and storage of water in the soil profile. Urban soils are frequently compacted as a result of construction activity, vehicle traffic and ongoing human interference. These conditions cause the loss of pore space and inhibit flow of water which results in poor drainage and increased surface runoff. The incorporation of biochar has the potential to drastically change these hydraulic properties, by improving soil structure and creating more pores for which the water can flow.

Biochar has an extremely porous structure that helps to increase soil aggregation and soil particle aggregation. Biochar can be added to urban soils to lower bulk density and provide extra pathways for water to flow. More porous areas allow for more rapid infiltration and smaller pores will hold moisture for longer. This combination allows for better infiltration of water into the soil and a greater amount of water is stored in the root zone.

Yields of hydraulic conductivity are frequently greater in amended soils than in unamended soils for biochar soils.The hydraulic conductivity of biochar soils is often higher than the hydraulic conductivity of unamended soils. The higher the hydraulic conductivity, the more free flow of water through the soil profile. This enhancement will be especially valuable in urban soils that are compacted and have reduced natural infiltration. Better hydraulic performance can help minimise standing water during rainfalls, and improve overall drainage efficiency(5).

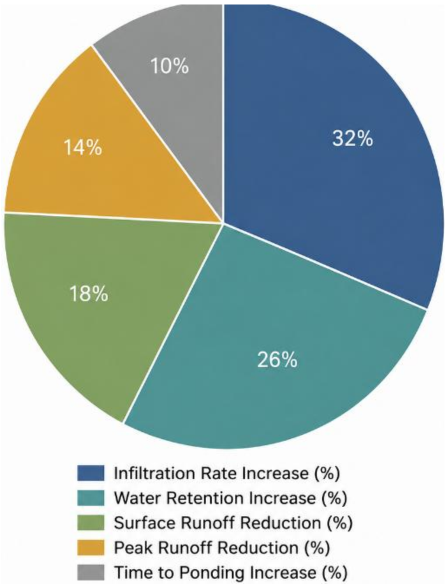
Biochar's effectiveness is dependent on the type of feedstock, the pyrolysis temperature, particle size, and application rates. The increased applications usually produce more increases in soil porosity and hydraulic conductivity. But in excess, it can actually change the structure of soils without adding value. It is therefore important to select the correct application rate to ensure optimal hydraulic efficiency and stability of the soil.

3.2 Flow and infiltration dynamics under rainfall conditions

When rainfall works its way into the soil surface and through the soil profile it is called infiltration. Urban soils are frequently compacted and there is limited infiltration due to the presence of extensive impervious surfaces. This means that extensive surface flow occurs and leads to flooding, erosion, and pollutant transport. Numerous studies have been conducted on biochar amendment for enhancing infiltration and minimising the generation of runoff.

Biochar amended soil typically has higher infiltration rates than other soils during rainy periods. Biochar has porous structure, which provides additional porosity and increases water penetrability. Better aggregation also ensures that there is soil porosity, limiting the tendency of soils to seal quickly during heavy rains. As a result, more of the precipitation seeps into the ground than runs off.

Biochar can be seen to have a significant effect on infiltration when there is heavy rain. Soils of cities are not always well draining and are likely to become saturated quickly, leading to a buildup of excess water and runoff. Biochar amended soils, in contrast, tend to have a longer soil water holding capacity before they become saturated. This helps to lower peak flows and make drainage facilities more efficient.
Better infiltration also helps recharge groundwater and promote vegetation growth by providing more water within the soil. One of the key ways that biochar manages stormwater in green infrastructure systems like rain gardens, bioswales, and bioretention cells is by enhancing infiltration. The decrease in the amount of runoff also reduces the volume of sediments, nutrients and contaminants being transported to nearby water bodies.
Biochar usually enhances infiltration, but environmental conditions like soil texture and amount of rainfall may affect the magnitude of the biochar effects. Soils with relatively high infiltration rates (typically sandy soils) can benefit to a moderate extent, while more improvement can be seen in compacted clay soils (higher infiltration rates after biochar application).



PIE CHART 1 Hydrological response of biochar-amended soils chart

3.3 Water-Holding Capacity Evaluation

Water holding capacity is the capacity of soil to retain water after it rains or has been watered. This is especially significant in urban environments where plants are often subjected to periods of over-watering and periods of drought. Urban soils are frequently compacted, low in organic matter, and poor in soil structure, which makes them less water-holding compared to healthy soils.
Biochar can enhance water-holding capacity of soil in a significant manner. Biochar is porous and has an internal pore structure that acts as a receptacle for water to be stored in the pores. The water is stored to be available to plants for longer than is the case in compacted soils. Consequently, plants on biochar-enhanced soil could have more water available in droughty periods.
Biochar also helps to increase soil water holding capacity and the percentage of fine pores in soil aggregates. These pores are filled with water in spite of gravity and still provide good air circulation to plant roots. The overall outcome is a more even soil moisture regime, resulting in healthy soil and microbial life.
Soil moisture data is often collected and indicates that biochar soils tend to hold moisture for longer after rain than non-biochar soils. This water may be saved for irrigation water use in urban landscapes and could help the resiliency of plants when water is scarce. This can be a significant advantage in urban areas where water conservation is a major environmental goal(6).
Increased water holding capacity also helps to manage stormwater, by slowing the release of water from the soil profile. Soil moisture may slowly replenish the atmosphere via evaporation and plant transpiration and not necessarily run off immediately. This way, the hydrological fluctuations are reduced and overall urban green infrastructure systems are better performing.

4. Heavy Metal Retention and Soil Remediation Processes

4.1 Mobility Behavior of Lead, Cadmium, and Zinc

Heavy metals are among the most common pollutants found in urban soils and stormwater runoff. Sources of contamination include vehicle emissions, tire and brake wear, industrial activities, construction materials, atmospheric deposition, and improper waste disposal. Lead (Pb), cadmium (Cd), and zinc (Zn) are of particular concern because they can accumulate in soils over long periods and pose risks to ecosystems and human health.

The mobility of heavy metals in soil depends on several environmental factors, including soil pH, organic matter content, moisture conditions, and mineral composition. Under unfavorable conditions, these metals can dissolve into soil water and move through the soil profile. This movement increases the likelihood of groundwater contamination and facilitates the transfer of pollutants into surrounding water bodies.

Lead generally exhibits relatively low mobility because it strongly binds to soil particles and organic matter. However, under acidic conditions, lead can become more soluble and available for transport. Cadmium is usually more mobile than lead and can migrate more readily through the soil profile, making it one of the most environmentally sensitive heavy metals. Zinc displays intermediate behavior, with mobility varying according to soil chemistry and environmental conditions.

Urban stormwater can accelerate the movement of these metals by transporting contaminated particles across impervious surfaces and depositing them in soil systems. Repeated accumulation may gradually increase metal concentrations in urban soils. Without effective remediation measures, these contaminants can affect plant growth, soil organisms, and water quality.

The application of biochar has emerged as an effective strategy for reducing heavy metal mobility. By altering soil chemical properties and providing additional adsorption sites, biochar can immobilize contaminants and limit their movement through the environment. Reduced metal mobility lowers environmental risks and supports the long-term restoration of degraded urban soils.

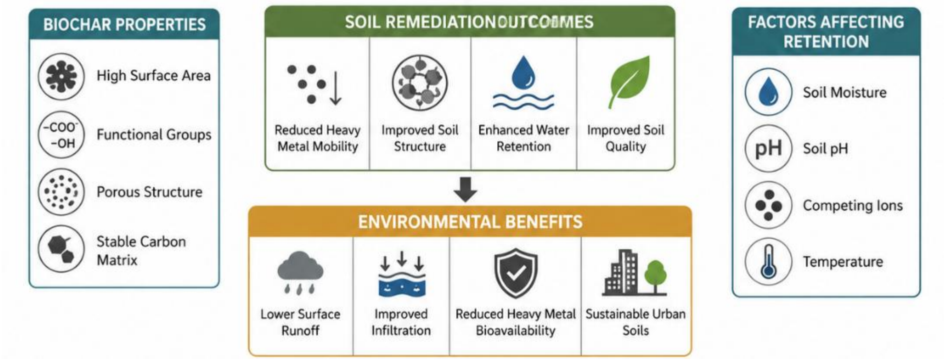


DIAGRAM 2 Soil remediation and metal retention processes

4.2 Adsorption Mechanisms Induced by Biochar Incorporation

Biochar reduces heavy metal mobility primarily through adsorption and immobilization processes. Its large surface area and highly porous structure provide numerous sites where metal ions can attach and become retained within the soil system. These characteristics make biochar an effective sorbent for a wide range of contaminants, including lead, cadmium, and zinc.

One important mechanism is surface adsorption. Heavy metal ions are attracted to functional groups located on the biochar surface, such as hydroxyl, carboxyl, and carbonyl groups. These functional groups form chemical interactions with metal ions, reducing their availability in soil water and limiting their movement through the soil profile.

Biochar can also increase soil pH, particularly when produced from agricultural residues at moderate to high pyrolysis temperatures. Higher soil pH often decreases the solubility of heavy metals, causing them to precipitate or become more strongly bound to soil particles. As a result, metals remain in less mobile forms that are less likely to contaminate groundwater.

Another important process involves ion exchange and complexation. Negatively charged surfaces on biochar can attract positively charged metal ions and hold them through electrostatic interactions. In addition, biochar can promote the formation of stable metal-organic complexes that further reduce contaminant mobility. These processes contribute to long-term metal stabilization within the soil.

Biochar incorporation may also support microbial communities that participate in soil remediation processes. Enhanced microbial activity can influence metal transformation and stabilization through biological and biochemical reactions. The combined effects of adsorption, precipitation, ion exchange, complexation, and microbial interactions make biochar a valuable tool for improving soil quality and reducing heavy metal risks in urban environments(7).

5. Results

5.1 Stormwater Retention Performance across Biochar Treatments

The results showed clear differences in stormwater retention among the biochar treatments. Plots amended with biochar consistently retained more water than the untreated control plots. As the biochar application rate increased, the amount of stormwater stored within the soil profile also increased. This improvement was mainly attributed to the porous structure of biochar, which enhanced soil porosity and created additional storage spaces for water.

The control plots exhibited rapid saturation during rainfall events, resulting in greater surface runoff and lower water retention. In contrast, the biochar-amended plots absorbed rainfall more effectively and delayed the onset of runoff generation. Medium and high biochar application rates demonstrated the greatest retention performance, indicating that sufficient biochar incorporation can significantly improve the capacity of urban soils to manage stormwater.

The improved retention performance was particularly noticeable during high-intensity rainfall events. While all plots experienced increased water input, the biochar-amended soils maintained greater storage capacity and reduced the volume of excess water leaving the site. These findings suggest that biochar can contribute to more resilient urban stormwater management systems by increasing the amount of water temporarily stored within the soil.

5.2 Comparative Infiltration and Runoff Outcomes

The comparison of infiltration and runoff outcomes revealed significant benefits associated with biochar application. Infiltration rates increased across all amended plots when compared with the untreated control. The improvement was most pronounced in plots receiving medium and high biochar application rates, where soil structure was noticeably enhanced. Increased pore connectivity allowed water to move more freely through the soil profile, reducing the likelihood of surface ponding during rainfall events.

The untreated plots showed lower infiltration rates due to compaction and limited pore space. Water accumulated on the soil surface more quickly, resulting in earlier runoff generation. In contrast, biochar-treated soils remained unsaturated for longer periods and continued to absorb water even during prolonged rainfall. This delayed saturation reduced runoff volumes and improved the overall hydrological performance of the site.

Runoff measurements demonstrated a clear inverse relationship between infiltration and surface water discharge. As infiltration increased, runoff volumes decreased. The high-rate biochar treatment produced the lowest runoff volumes, indicating the strongest capacity for stormwater control. The medium-rate treatment also performed well and achieved results that were close to those observed in the high-rate treatment, suggesting that substantial benefits can be achieved without excessive biochar application.

The reduction in runoff has important environmental implications. Lower runoff volumes reduce pressure on urban drainage systems and decrease the risk of localized flooding. In addition, reduced surface flow limits the transport of sediments, nutrients, and contaminants into nearby waterways. This contributes to improved water quality and supports the broader objectives of sustainable urban water management.

Soil moisture monitoring further supported these findings. Biochar-amended plots retained moisture for longer periods after rainfall events, while control plots experienced faster drying. The increased water availability can support vegetation growth and improve the performance of green infrastructure systems such as rain gardens and bioswales. Overall, the results indicate that biochar amendment is an effective strategy for enhancing infiltration, reducing runoff, and improving the hydrological function of degraded urban soils.

5.3 Heavy Metal Mitigation Effectiveness

The study demonstrated that biochar amendment significantly improved the retention of heavy metals within the soil. Concentrations of lead (Pb), cadmium (Cd), and zinc (Zn) detected in drainage water were generally lower in biochar-treated plots than in the control plots. This indicates that biochar reduced the mobility of these contaminants and limited their transport through the soil profile.

Lead showed the highest retention efficiency among the metals evaluated. Its strong affinity for biochar surfaces and soil organic matter contributed to effective immobilization. Cadmium, which is generally more mobile in soil environments, also showed reduced movement following biochar application. Zinc concentrations decreased as well, although the magnitude of reduction varied depending on rainfall intensity and soil moisture conditions.

Higher biochar application rates resulted in greater heavy metal retention. The large surface area and abundance of adsorption sites provided by biochar enhanced the capacity of the soil to capture and retain metal ions. In addition, the increase in soil pH associated with biochar incorporation contributed to lower metal solubility and reduced contaminant mobility.

These findings confirm that biochar can serve a dual purpose in urban soil management. In addition to improving stormwater performance, it can also support soil remediation by reducing the environmental risks associated with heavy metal contamination.

6. Conclusion

6.1 Key Environmental Engineering Findings

This study evaluated the effectiveness of agricultural biomass-derived biochar as a soil amendment for improving stormwater management and environmental quality in urban soils. The results demonstrated that biochar significantly enhanced the physical, hydrological, and contaminant retention properties of degraded urban soils. These improvements support the growing interest in biochar as a practical solution for addressing multiple environmental challenges within urban landscapes.

One of the most important findings was the improvement in soil hydraulic performance following biochar incorporation. The porous structure of biochar increased soil porosity and reduced compaction, allowing water to infiltrate more effectively. Enhanced infiltration reduced the accumulation of surface water during rainfall events and lowered the volume of runoff generated from the study plots. These outcomes indicate that biochar can help mitigate urban flooding risks by improving the ability of soils to absorb and store rainfall.

The study also showed that biochar increased soil water-holding capacity. Amended soils retained moisture for longer periods following rainfall events, creating more stable soil water conditions. Improved water retention can benefit urban vegetation by providing a more reliable supply of moisture during dry periods. This characteristic is particularly valuable in cities where climate variability and water scarcity are becoming increasingly important concerns.

Another significant finding was the ability of biochar to reduce heavy metal mobility. Concentrations of lead, cadmium, and zinc in drainage water decreased after biochar application, demonstrating improved contaminant retention. The combination of adsorption, ion exchange, surface complexation, and pH modification contributed to the immobilization of these pollutants. By limiting heavy metal movement through the soil profile, biochar can reduce the risk of groundwater contamination and improve the environmental quality of urban ecosystems.

The statistical analysis provided additional support for the effectiveness of biochar treatments. Positive relationships were observed between biochar application rate and environmental indicators such as infiltration, water retention, and heavy metal immobilization. At the same time, runoff volume decreased as biochar rates increased. These findings confirm that biochar is a major factor influencing the environmental performance of urban soils.

Overall, the study demonstrates that agricultural biomass biochar can simultaneously improve stormwater management, enhance soil quality, and support urban soil remediation. Its ability to address multiple environmental objectives makes it a valuable tool for sustainable urban environmental engineering and green infrastructure development.

6.2 Implications for Sustainable Urban Infrastructure Planning

The findings of this study have important implications for the design and management of sustainable urban infrastructure. Biochar can be incorporated into a wide range of green infrastructure systems to improve their long-term environmental performance and resilience.

Key implications include:

- Improved stormwater infiltration and reduced surface runoff in urban areas.
- Enhanced performance of rain gardens, bioswales, bioretention cells, and other green infrastructure systems.
- Increased soil water storage, reducing irrigation requirements for urban landscapes.
- Greater resilience to extreme rainfall events and changing climate conditions.
- Reduced transport of pollutants into rivers, lakes, and groundwater resources.

- Improved retention of heavy metals and other contaminants within urban soils.
- Productive use of agricultural waste materials through biochar production.
- Long-term carbon storage and support for climate change mitigation efforts.
- Lower maintenance requirements for stormwater management systems due to improved soil functionality.
- Support for sustainable city planning strategies that integrate environmental protection with urban development.

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Conflicts of interest

The authors have no conflicts of interest to declare

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