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*Review*

# A Review on Carbon-Negative Woody Biomass Biochar System for Sustainable Urban Management in the United States of America

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**Abstract:** It is essential to emphasize the significant impacts of climate change, which are evident in the form of severe and prolonged droughts, hurricanes, snowstorms, and other climatic disturbances. These challenges are particularly pronounced in urban environments and among human populations. The situation is further aggravated by the increasing utilization of available open spaces for residential and industrial development, leading to heightened energy consumption, elevated pollution levels, and increased carbon emissions, all of which negatively affect public health. The primary objective of this review article is to provide a comprehensive evaluation of current research, with a particular focus on the innovative use of residual biomass from urban vegetation for biochar production in the United States. This research entails an exhaustive review of existing literature to assess the implementation of a carbon-negative wood biomass biochar system as a strategic approach to sustainable urban management. By transforming urban wood waste—including tree trimmings, construction debris, and storm-damaged timber—into biochar through pyrolysis, a thermochemical process that sequesters carbon while generating renewable energy, we can leverage this valuable resource. The resulting biochar offers a range of co-benefits: it enhances soil health, improves water retention, reduces stormwater runoff, and lowers greenhouse gas emissions when applied in urban green spaces, agriculture, and land restoration projects. This review highlights the advantages and potential of converting urban wood waste into biochar while exploring how municipalities can strengthen their green ecosystems. Furthermore, it aims to provide a thorough understanding of how the utilization of woody biomass biochar can contribute to mitigating urban carbon emissions across the United States.

**Keywords:** urbanization; biochar; pyrolysis; urban management; the United States

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## 1. Introduction

The rapid pace of urbanization has engendered a myriad of environmental challenges globally, notably the erosion of natural green spaces [1]. This reduction adversely affects ecosystems, precipitates biodiversity loss, deteriorates air quality, and compromises the overall well-being of urban inhabitants by disrupting ecological equilibrium, exacerbating the urban heat island phenomenon, and diminishing the aesthetic quality of urban landscapes. A critical examination of climate change impacts—such as protracted droughts, hurricanes, snowstorms, and other climatic anomalies—is essential, particularly concerning their repercussions for urban environments and human populations [2].

The catastrophic wildfires that ravaged California in early 2025 serve as a poignant illustration of the vulnerabilities that urban areas face, reiterating a concerning trend also observable in states such as Hawaii, Washington, and Oregon, as well as internationally [2].

The pressing need for developing and implementing effective mitigation strategies is imperative to diminish the severity and frequency of such climatic events, safeguard at-risk communities, and bolster the resilience of both urban and ecological systems.

Over the past three centuries, the United States has undergone monumental urban and industrial growth [3], now ranking as the third most populous nation with a population exceeding 333 million, over 75% urbanized [2–4]. Global climate change continues to exert considerable strain on urban ecosystems, with expectations for these pressures to escalate in the foreseeable future.

The interplay between urbanization and climate change is increasingly acknowledged as complex and multifaceted, encompassing various contributing factors. Principal elements driving this correlation include population growth, industrial expansion, economic development, escalating energy demand, reliance on fossil fuels, shifts in land use, and widespread deforestation. Furthermore, urban planning and infrastructure are integral to understanding this intricate relationship [5–7].

As urban areas expand, they exert significant pressure on energy resources, resulting in increased waste generation, heightened transportation demands, and necessitate extensive infrastructure development. These interrelated dynamics contribute to elevated greenhouse gas emissions, depletion of natural resources, and accelerated environmental degradation [8].

Moreover, the nexus between rapid urbanization and climate change intensifies environmental degradation and exacerbates social vulnerabilities, particularly within urban locales that serve as both significant contributors to and victims of the global climate crisis [9]. Experts warn that the ramifications of climate change extend beyond urban-centric challenges; they threaten biodiversity, heighten the risk of species extinction, and compromise critical ecosystem functions. This disruption endangers the stability of natural systems, undermining essential ecological services relied upon by human populations, including clean air, potable water, food security, climate regulation, and disease control [5]. Research indicates that climate change amplifies existing urban challenges, leading to increased heat stress, water scarcity, and extreme meteorological events. Marginalized populations in urban settings are disproportionately affected, as they frequently lack the requisite resources for efficacious adaptation [2,10–13].

Addressing climate change necessitates a multifaceted strategy that integrates both the reduction of greenhouse gas emissions and approaches for atmospheric $CO_2$ removal, all while aiming for net-zero emissions [14]. Projections suggest that, by the end of the 21st century, the urban population could constitute between 60% and 92% of the global total, underscoring the critical importance of urban soil health and functionality [14].

A thorough understanding of the complexities inherent in the urban climate crisis is essential for effectively addressing the challenges posed by rapid urbanization and intensifying climate change. This understanding enables the development of targeted, sustainable, and equitable solutions that tackle environmental issues while simultaneously addressing the socio-economic disparities exacerbated by these interlinked crises. Neglecting the detrimental effects of urbanization on climate dynamics risks leading to severe outcomes, including exacerbated social inequality, economic instability, and persistent environmental degradation. An integral adaptation strategy in response to climate change is the incorporation of green infrastructure, which encompasses networks of natural and semi-natural areas—both green (vegetated or soil-covered) and blue (water-covered). This network not only preserves but also enhances ecosystem functions [15,16].

Urban forestry emerges as an effective carbon-negative strategy, amplifying carbon sequestration, lowering atmospheric $CO_2$ concentrations, and bolstering long-term climate resilience in urban contexts. The utilization of woody biomass is pivotal for carbon storage, as urban vegetation plays a crucial role in absorbing atmospheric carbon dioxide and sequestering it in plant biomass and soil, thereby contributing significantly to climate change mitigation.

In this context, biochar is gaining traction as a critical medium for carbon sequestration. This carbon-dense material is produced from biomass sources, including woody and agricultural residues, through pyrolysis at temperatures ranging from 300 to 700 °C in low-oxygen or oxygen-depleted environments. Various methodologies such as torrefaction, microwave treatment, gasification, flash carbonization, hydrothermal carbonization, slow pyrolysis, and fast pyrolysis can be employed to synthesize biochar [17–19].

Converting biomass into biochar not only presents an opportunity to mitigate climate change but also enhances forest and soil health, reduces wildfire risks, strengthens ecosystem services, and supports the revitalization of rural economies [20]. Biochar is characterized by its chemical stability, elevated carbon concentration, and low levels of oxygen and hydrogen, rendering it environmentally durable. It can be produced from multiple feedstocks, including forest waste, agricultural residues, manure, and green waste [2,21–24].

The production of biochar substantially contributes to greenhouse gas emission reductions by transforming the organic carbon in biomass into a more stable form, thereby preventing the release of $CO_2$ and $CH_4$ that occurs during natural decomposition processes [25]. This holistic approach aligns with global efforts to manage carbon emissions effectively and enhance overall ecosystem resilience.

Effective implementation of biochar systems can yield a significant reduction in global greenhouse gas emissions, estimated at approximately 3.4 to 6.3% in $CO_2$ equivalents, with nearly half of this reduction a result of permanent carbon sequestration [23]. Recent investigations suggest that downed timber, particularly loblolly pine that has been exposed to atmospheric conditions for up to six months, produces biochar with enhanced physicochemical characteristics and superior capacity for lead ($Pb^{2+}$) adsorption. This positions biochar as a viable solution for environmental remediation tasks. Notably, the study highlights the influence of tree maturity and exposure duration on the biochar's efficacy, providing critical insights for the optimization of forest biomass feedstock tailored for water treatment applications [25].

Additionally, the application of biochar is gaining recognition as a potent strategy for carbon sequestration and greenhouse gas mitigation, effectively curtailing emissions of $CO_2$, $CH_4$, and $N_2O$ across varied ecosystems. This mitigation is facilitated through modifications in soil physicochemical properties coupled with the regulation of microbial functional genes integral to carbon and nitrogen cycling [26].

Wood-derived biochar, characterized by a higher lignin content, generally exhibits a greater surface area compared to grass-based alternatives, leading to the development of more organo-mineral complexes that function as nutrient reservoirs for microbial populations. This, in turn, augments microbial activity and significantly influences soil greenhouse gas emissions [27]. Comprehensive research has demonstrated that biochar application is both a cost-effective and efficient methodology for supporting climate change mitigation and adaptation efforts. By enhancing or preserving soil quality, biochar contributes to maintaining or improving crop yield in diverse agricultural settings, including upland and paddy fields under shifting climatic conditions [28].

Transforming urban wood waste into biochar represents a sustainable management approach for addressing excess biomass generated from tree trimmings, storm debris, and construction waste. This conversion process not only bolsters urban habitats but also presents avenues for alternative energy generation while diverting woody materials from landfills, thus enhancing ecosystem services [2]. Moreover, biochar derived from urban forestry and waste plays a crucial role in developing urban green infrastructures, such as green roofs, permeable pavements, green walls, and green parking lots. Incorporating biochar into substrate blends offers multiple benefits, including enhanced moisture retention, improved nutrient availability, increased plant growth, and significant carbon sequestration potential [2].

The primary aim of this review article is to conduct a comprehensive assessment of the existing literature, particularly focusing on the innovative applications of residual biomass from urban vegetation for biochar production in the United States. The specific objectives of this review are:

(i) To evaluate the carbon-negative potential of biochar systems derived from woody biomass and their impact on mitigating greenhouse gas emissions within the urban sustainability context in the United States.
(ii) To analyze the environmental, economic, and social co-benefits associated with integrating biochar systems into urban waste management strategies, soil enhancement practices, and climate adaptation plans.
(iii) To identify key challenges, policy gaps, and opportunities for scaling the utilization of woody biomass biochar in urban planning and infrastructure development, thereby fostering long-term sustainable urban management.

This exploration underscores the significant potential and myriad advantages of converting urban woody biomass, often treated as waste and disposed of in landfills, into a valuable resource that can rejuvenate urban green spaces and simultaneously generate bioenergy.

## 2. Urbanization and Climate Change

### *2.1. Urbanization and Its Influence on Climate Change*

Urbanization significantly contributes to climate change, primarily through rising temperatures in urban environments due to increased surface heat retention and altered land use (Figure 1). The rapid urbanization of populations, coupled with the intensifying repercussions of climate change, presents formidable challenges to environmental sustainability and public health. Over the last two centuries, anthropogenic activities have significantly influenced climate dynamics by altering the Earth's surface albedo and the amount of solar radiation absorbed [29].

The impact on albedo has primarily originated from land use changes, particularly through deforestation and urbanization [30]. Vegetation, including trees, effectively absorbs solar radiation and reflects less compared to urbanized or barren landscapes, which exacerbates global warming. Projections indicate that, by 2050, around 70% of the global population will inhabit urban environments, up from approximately 56% (around 4.4 billion persons) in recent years [31,32].

In the United States, urbanization is particularly pronounced, with 82.66% of the population residing in urban areas as of 2020. This trend, initiated by early industrialization, is expected to push urban residency close to 90% by mid-century, transitioning urban populations to outnumber rural ones—a shift that began as early as the 1910s [33,34]. New York leads U.S. cities with 8.3 million residents, while California has the highest total of urban inhabitants. Though the District of Columbia is fully urban, other states like Maine, Mississippi, Montana, and West Virginia maintain predominantly rural demographics.

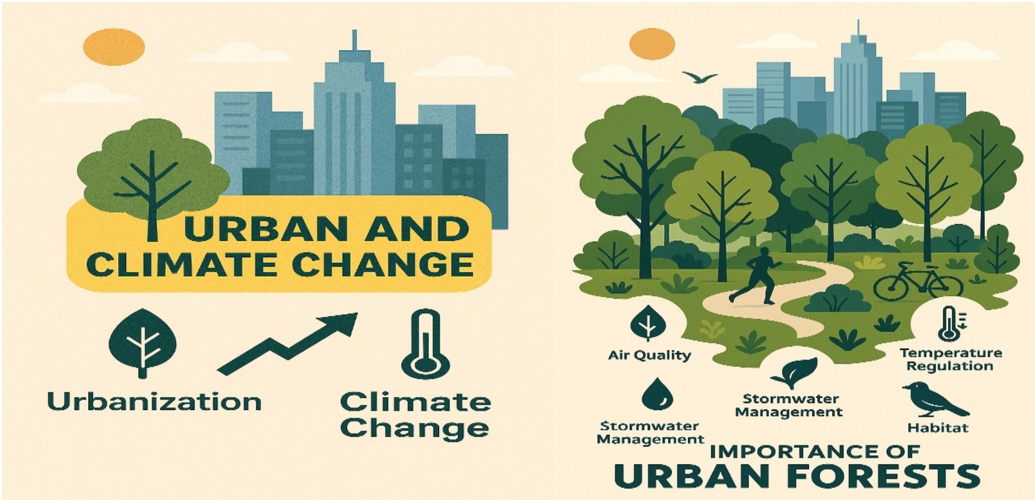


**Figure 1.** Urban environment, climate change, and importance of urban forest.

The extensive urbanization and migration trends across North America have precipitated a range of issues, including pollution, traffic congestion, and significant reductions in green spaces [35]. These challenges place considerable stress on natural resources, urban infrastructure, and overall living conditions [9]. As urbanization-related challenges escalate, there is an urgent need for resilient, adaptive solutions. Urban areas are significant contributors to global greenhouse gas emissions, accounting for approximately 75% of carbon dioxide emissions, despite representing merely 2% of the Earth's land area and housing over half of the global population [36]. Without substantial mitigation efforts, urban greenhouse gas emissions are projected to rise markedly by 2050, driven by continuous population growth, urban expansion, and increasing demands for infrastructure and services. The degree of this rise will depend on various development scenarios and the effectiveness of cities' climate strategies.

Emissions of carbon dioxide predominantly emanate from urban areas, fueled by a combination of factors, including the increase in impervious surfaces, changes in land use, industrial activities, transportation, and higher energy consumption [37]. As urbanization advances, it reshapes land use patterns and exacerbates waste generation, thereby magnifying the drivers of global climate change. Atmospheric concentrations of greenhouse gases continue to rise, with carbon dioxide averaging 410 ppm annually. This interplay between elevated carbon dioxide levels and rising temperatures further exacerbates climate change impacts [2]. For instance, 2021 marked the sixth warmest year recorded, with global temperatures averaging 0.84 °C (1.51 °F) above the 20th-century baseline [26]. Without strategic planning and investment in low-carbon technologies, these trends will likely impede future mitigation efforts aimed at reducing greenhouse gas emissions.

### *2.2. Urban Heat Island (UHI) Effect*

Urban heat islands (UHIs) are phenomena wherein urbanized areas display significantly higher temperatures compared to surrounding rural environments [38]. This temperature discrepancy arises from various interrelated factors that enhance air temperatures within urban contexts relative to their less developed counterparts [39].

The UHI effect is characterized by altered thermal gradients, exhibiting elevated daytime temperatures coupled with diminished nighttime cooling in urban zones [9]. The urban fabric and architectural configurations critically influence this effect. Elements such as high-rise buildings, densely packed structures, and narrow thoroughfares create "urban canyons" that disrupt natural airflow. This impediment to ventilation fosters the accumulation of heat and air pollutants, thereby exacerbating local temperature increases.

Moreover, the UHI effect is shaped by a confluence of socio-economic and biophysical parameters, including population density, land use, construction materials, vegetation cover, and energy consumption patterns [40]. For example, in cities like Los Angeles, accelerated urbanization has substantially altered the natural landscape. The proliferation of impervious surfaces, road infrastructure, and the supplanting of vegetative cover with materials like asphalt and concrete have enhanced the urban environment's capacity to absorb and retain thermal energy. These materials tend to store heat during the daytime and gradually release it throughout the night, resulting in elevated nocturnal temperatures. As a consequence, Los Angeles has seen a marked intensification of the UHI effect, manifesting significant implications for local climate dynamics and public health [41].

The determinants of the UHI effect can vary considerably across different geographies, urban areas, and climate regimes, resulting in diverse expressions of this phenomenon. Thus, the intensity and characteristics of UHIs can fluctuate not only between different regions but also within the same urban area over time [42]. This variability is often highlighted in seasonal and diurnal temperature patterns, with distinct peaks observed between day and night, as well as across different seasonal cycles.

### *2.3. Urbanization and Local Climate Shifts*

Urbanization significantly alters local temperature dynamics, primarily through enhanced heat retention and the reduction of vegetative cover [43,44]. This modification contributes to the urban heat island (UHI) effect, disrupting the thermal equilibrium between urban and adjacent rural areas. Such disturbances in thermal structure can influence atmospheric circulation and moisture distribution, ultimately leading to larger-scale regional climate shifts [45]. These alterations may increase the frequency and intensity of extreme weather phenomena.

Furthermore, urbanization profoundly affects local precipitation patterns by interfering with natural hydrological cycles [9,44]. The dominance of impervious surfaces, such as concrete and asphalt, limits groundwater recharge and increases surface runoff, heightening the risk of urban flooding, particularly during intense rainfall events [45]. For instance, research in Atlanta, USA, illustrates how urbanization has critically reshaped local precipitation dynamics, resulting in more intense rainfall and concentrated storm activity linked to urban expansion [46].

The climatic changes induced by urbanization are likely to amplify both the prevalence and severity of extreme weather events, including heatwaves, droughts, storms, hurricanes, and severe rainfall episodes. These extreme events pose significant risks to communities, threatening infrastructure, disrupting agricultural productivity, and adversely impacting natural ecosystems [15,18].

## 3. The Role and Importance of Urban Forests

### *Ecological and Social Benefits of Urban Forests*

Urban trees are integral to urban environmental quality, significantly mitigating air pollution, regulating microclimates, and sequestering atmospheric carbon dioxide. These green infrastructures enhance stormwater management, thereby alleviating flood risks and enhancing water quality. Furthermore, urban forests bolster biodiversity by providing essential habitats for a variety of species, including avifauna, beneficial insects, and other wildlife within urban landscapes.

The ecological advantages of urban forestry extend to human health and social well-being. Urban trees create vital recreational spaces, reduce psychological stress through nature exposure, and contribute to both the social fabric and economic vitality of communities [2].

Provisioning services are a primary benefit of urban forests, supplying tangible resources such as food, clean water, fresh air, forest products, and accessible green spaces. Regulating services are critical for moderating ecological processes, including climate stabilization, flood attenuation, disease vector control, waste decomposition, and maintaining hydrological quality [47,48].

Moreover, urban forests provide cultural services that yield non-material benefits, such as recreational opportunities, aesthetic enhancements, mental health promotion, and spiritual enrichment. Supporting services, essential for ecosystem functionality, encompass soil formation, nutrient cycling, and photosynthetic activity. Collectively, these services underscore the irreplaceable role of urban forests in fostering sustainable, resilient, and livable urban environments [49,50].

Additionally, the atmospheric benefits of urban trees include improving air quality through the absorption of pollutants and reduction of $CO_2$ levels [51]. Mature trees act as carbon sinks, sequestering $CO_2$ as biomass within their structure. Urban trees mitigate air pollution via two principal mechanisms: direct uptake of gaseous pollutants through leaf stomata and trapping particulate matter on their surfaces [17]. Studies indicate that urban trees in the United States remove approximately 711,000 metric tons of air pollutants annually, translating to an economic value of about USD 3.8 billion.

In 2010, forests and trees across the contiguous United States were instrumental in enhancing air quality by removing approximately 17.4 million tons of air pollutants. This reduction is projected within a range of 9.0 to 23.2 million tons. The associated public health benefits from this air purification have been valued at around USD 6.8 billion, with estimates ranging from USD 1.5 billion to USD 13.0 billion. These evaluations stemmed from sophisticated computer simulations employing localized environmental data, underscoring the essential role of forests in public health protection and environmental improvement [18].

In terms of carbon dynamics, urban vegetation plays a pivotal role in carbon sequestration, absorbing atmospheric $CO_2$ and storing it in both biomass and soil [17–19].

Current assessments indicate that urban trees across the continental United States sequester roughly 22.8 million tons of carbon annually, translating to a monetary value of approximately USD 460 million. Furthermore, they collectively store about 700 million tons of carbon, valued at around USD 14.3 billion [19]. Notably, carbon storage capacities in urban settings vary greatly, with New York City holding about 1.2 million tons compared to Jersey City's 19,300 tons. This quantification not only establishes a scientific foundation for the role of urban forests in mitigating atmospheric $CO_2$ levels but also aids urban planners and policymakers in recognizing the climate benefits of urban forestry [19].

Additionally, urban forest ecosystems, incorporating trees, soil, and ground cover, are vital for effective stormwater management. They significantly reduce stormwater runoff volumes, attenuate rainfall intensity, delay the onset of runoff, enhance soil infiltration, and bolster the water storage capacity of soils [52]. Integrating trees into stormwater management frameworks can amplify the efficacy of green stormwater infrastructure (GSI) practices by delivering multiple hydrological benefits. Consequently, urban forests play a crucial role in improving water retention, filtration, and runoff control.

## 4. Converting Urban Forest Biomass into Biochar

### *4.1. Biochar as a Sustainable Byproduct of Urban Forest Management*

Biochar is a carbon-dense solid generated from biomass—such as woody and agricultural residues—through a thermochemical process known as pyrolysis, conducted under low or virtually absent oxygen conditions at temperatures ranging from 300 to 700 °C [23]. Pyrolysis effectively decomposes organic matter, producing three principal byproducts: biochar, bio-oil, and syngas [53–55]. This method not only transforms waste materials into valuable resources, but it also offers a sustainable approach to carbon sequestration using various production techniques. Biochar production technology overview has shown in Figure 2.

The term "pyrolysis" is derived from the Greek words "pyro," meaning fire, and "lysis," indicating decomposition. This technology is classified into three primary categories based on operational parameters: slow pyrolysis, fast pyrolysis, and flash pyrolysis.

i. Slow Pyrolysis: Characterized by extended reaction durations—spanning from minutes to days—this approach yields approximately 35% biochar, 30% bio-oil, and 35% syngas [56]. While slow pyrolysis has a long history of enhancing char production, it is less efficient for high-quality bio-oil due to the negative impacts of prolonged residence times on its yield and characteristics.
ii. Fast Pyrolysis: This methodology employs rapid heating of biomass to achieve high temperatures, providing yields of 15–25% biochar, 60–75% bio-oil, and 10–20% syngas [57]. Fast pyrolysis is conducted under low-temperature conditions, with high heating rates and short residence times, to optimize liquid yield. This approach has gained traction for its potential to generate liquid fuels and facilitate their conversion into high-value chemicals, thereby enhancing the economic feasibility of pyrolysis systems.
iii. Flash Pyrolysis: This variant rapidly heats biomass within seconds at varying pressures, optimizing conditions for maximizing yield—potentially up to 60% biochar or 70% bio-oil [57,58].

The bio-oil produced during pyrolysis contains a complex mixture of oxygenated organic compounds such as esters, ethers, aldehydes, ketones, phenols, carboxylic acids, and alcohols, which can function as viable energy sources. Upgrading this bio-oil into high-value chemicals can significantly augment the economic aspects of the pyrolysis process [57].

Meanwhile, the generated syngas, which consists of hydrogen ($H_2$), carbon monoxide (CO), carbon dioxide ($CO_2$), methane ($CH_4$), and various volatile organic compounds [23,57], can serve as an energy source for subsequent pyrolysis stages or be converted into thermal energy for dry biomass applications [59]. Notably, syngas with low to medium heating values can be recirculated to provide energy for biomass pyrolysis or be channeled as a fuel for gas engines to produce electricity or heat for localized systems [23].

The characteristics of biochar, influenced by feedstock type and pyrolysis conditions, render it a prominent byproduct of biomass pyrolysis. Rich in carbon, biochar's stability allows for significant carbon sequestration potential. Besides carbon, it encompasses hydrogen, oxygen, and a range of minerals including nitrogen, phosphorus, and sulfur, contingent on the initial biomass feedstock [23]. Research indicates that both feedstock selection and pyrolysis conditions critically shape the resultant biochar properties [23,60–63].

### 4.2. Effect of Feedstock on Biochar Properties

The chemical composition of feedstock and the pyrolysis temperature are critical determinants of biochar characteristics. Each biomass feedstock has a distinct elemental profile, which leads to varying thermal degradation behaviors across different pyrolysis temperatures [23]. A comprehensive understanding of biochar derived from diverse biomass materials and under varying production conditions is essential for evaluating its effects on soil properties and nutrient dynamics in crops. Thus, a thorough characterization of biochar properties is imperative before its deployment in agricultural and environmental contexts.

A range of biomass sources—including wood, crop residues, switchgrass, organic wastes, and animal manure—can serve as feedstocks for biochar production [64]. The feedstock composition is primarily made up of vital organic constituents such as cellulose, hemicellulose, and lignin, each exhibiting unique decomposition kinetics. These components play a significant role in determining the appropriate pyrolysis temperatures and choice of feedstock for effective biochar and biofuel production [23,61–66].

Research by Yang et al. (2007) [67] reveals that cellulose and hemicellulose typically decompose within the temperature range of 220–400 °C, while lignin shows considerable resistance to thermal degradation above this threshold. Biochar is predominantly generated from the lignin fraction of biomass, whereas bio-oil production is more closely associated with cellulose when pyrolysis occurs at 500 °C. Moreover, prior investigations have indicated that biochar produced from woody feedstocks with elevated carbon concentrations tends to exhibit a larger surface area and higher carbon content [68]. For example, biochar derived from wood residues with a high heating value (HHV) is comparable to subbituminous coal, in contrast to biochar from rice residues, which aligns more with lignite [69].

In conclusion, the interplay between feedstock composition and pyrolysis conditions is crucial for optimizing both biochar production and its potential applications in bolstering soil health and enhancing agricultural productivity.

### 4.3. Effect of Pyrolysis Temperature on Biochar Properties

The characteristics of biochar are significantly influenced by both the type of feedstock utilized and the specific pyrolysis conditions, including parameters such as temperature, heating rate, and residence time. Research indicates that the carbon content in biochars increases with pyrolysis temperature, with measured values of 58%, 62%, and 64% at 300, 500, and 700 °C, respectively. This trend suggests a more pronounced carbonaceous character as temperature escalates [23].

Biochar produced at higher pyrolysis temperatures demonstrates improved aromaticity and diminished polarity [70]. X-ray diffraction analyses reveal that higher pyrolysis temperatures lead to the degradation of cellulose while enhancing the crystalline mineral components within the biochar matrix. According to studies by Ahmad et al. (2012) [71], elevated temperatures not only boost carbon content but also cause reductions in hydrogen, nitrogen, and oxygen levels, indicating more effective carbonization processes.

Furthermore, the volatilization of nitrogen at greater temperatures contributes to lower nitrogen content while simultaneously increasing the cation exchange capacity (CEC) [72], surface area, and ash content of the biochar [73].

Typically, biochars display relatively high CEC due to the negatively charged surface, enabling them to attract soil cations effectively [23]. Higher pyrolysis temperatures result in marked increases in porosity and surface area, leading to a greater proportion of finer biochar particles and a diverse distribution of pore sizes, which collectively enhance the material's adsorption capabilities [74,75].

The ash content of biochar generally increases with rising pyrolysis temperatures due to the concentration of mineral compounds during the pyrolysis process [76]. Additionally, the pH of biochar tends to elevate with increasing pyrolysis temperature as alkali salts separate from organic compounds and acidic functional groups diminish, in parallel with an increase in basic functional groups [77,78]. Consequently, both the feedstock source and pyrolysis temperature are critical in dictating the final properties of biochar. A variety of biochar production techniques, especially in the US, are mentioned in Figure 3.

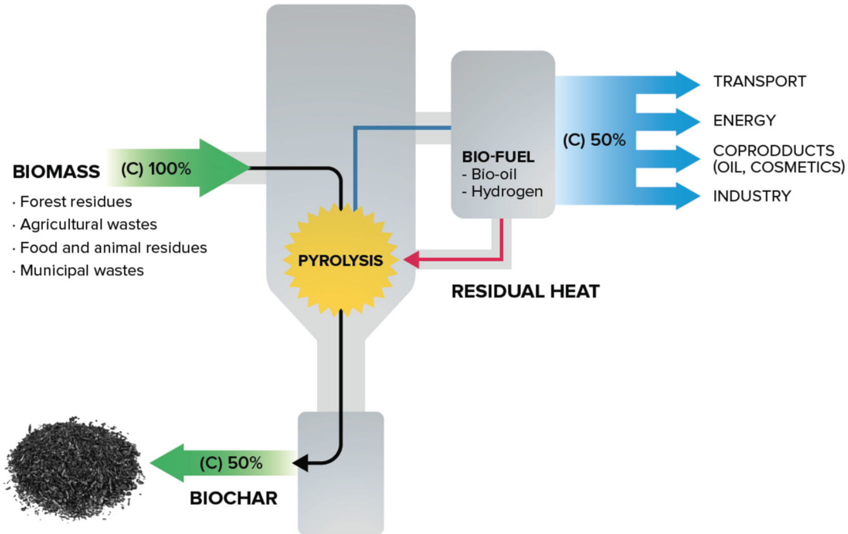


**Figure 2.** Biochar production diagram. International Biochar Initiative (IBI).


**Figure 3.** Biochar production technologies for forest feedstock.

## 5. Applications of Biochar in Urban Infrastructure

### *5.1. Enhancing Urban Soil Health with Biochar*

Urban trees encounter significant challenges in their growth, especially when rooted in restricted soil environments typical of urban settings, such as parking lots and roadside plantations [79]. The quality of urban soils is pivotal for supporting diverse forms of vegetation, microbial communities, and microfauna essential for ecosystem functionality [80].

One effective approach to ameliorate soil quality is the integration of biochar. Research indicates that biochar application enhances soil structure and increases water retention, which is critical for sustaining plant health in urban gardens—particularly during drought periods. Studies have shown that biochar-amended plots exhibit greater moisture retention during protracted dry spells [80]. A controlled greenhouse experiment further demonstrated that biochar contributed to increased soil macroaggregation and the formation of mesopores, thus improving water availability for plants. Consequently, plants under drought stress experienced a remarkable 39% increase in biomass and water use efficiency attributed to these structural developments. Therefore, biochar emerges as a robust strategy for enhancing drought resilience within urban green spaces.

The incorporation of biochar in urban soils not only improves drought resilience but also fortifies the vigor and robustness of trees in amended soils. A comprehensive meta-analysis assessing the impact of biochar on forest restoration revealed an average increase of 41% in tree biomass with biochar application [81]. Although results may vary according to environmental conditions, specific tree species, and cultivation settings (e.g., nursery versus forest environments), consistent application rates of biochar up to 20% of soil volume have consistently yielded positive outcomes across diverse studies.

A recent investigation assessed the effects of various soil amendments—namely biochar (BC), biosolids (BS), wood chips (WC), compost (COM), aerated compost tea (ACT), and nitrogen plus potassium fertilizer (NK)—on three types of urban soils and the growth performance of tree saplings [82]. The findings revealed that biosolids effectively decreased soil pH while elevating nitrogen availability, mineralization rates, and microbial respiration. In contrast, biochar was found to substantially augment total organic carbon levels. Among the different treatments, tree growth was notably enhanced—particularly in species such as Acer saccharum and Gleditsia triacanthos—when either biosolids or biochars were applied. Importantly, while nitrogen content was a crucial factor influencing most treatments, biochar demonstrated its effectiveness in promoting growth even with lower nitrogen levels. These results underscore the potential of biosolids and biochar as viable amendments for improving urban soil conditions and facilitating healthy tree development in urban areas.

The research conducted by Zwart and Kim (2012) [83] elucidates the efficacy of biochar as a soil amendment in mitigating stem lesions inflicted by Phytophthora species—widespread and virulent plant pathogens. Seedlings cultivated in biochar-enhanced soils exhibited markedly lower disease severity and diminished lesion progression compared to those in controls without biochar. This finding underscores biochar's dual role: not only does it improve the soil's physical properties and chemical profile, but it may also exert biological effects that suppress pathogen virulence or fortify host plant defense responses. The study highlights biochar's potential as a sustainable strategy for managing soilborne diseases, particularly relevant in urban settings and reforestation projects. Its capability to combat Phytophthora reinforces its importance in enhancing plant health and resilience under stress conditions, thereby advocating for its integration into tree planting and nursery operations as a preemptive defense against root and stem pathogens.

In urban landscaping, gardening, and turf management—practices that are highly visible to the public—there are significant opportunities to showcase the advantages of biochar application. Efficient water management is critical for sustaining healthy turf and promoting water conservation, particularly on expansive sports fields. Biochar's ability to improve soil moisture retention allows for reduced irrigation requirements without compromising turf quality, thus aligning with sustainability goals. Currently, approximately 70% of water usage in U.S. residential areas is attributed to turfgrass irrigation. Research indicates that optimizing irrigation strategies for tall fescue grass, especially in arid regions, can substantially contribute to community water conservation efforts [84]. Additionally, the seasonal peaks in municipal water consumption are frequently linked to landscape irrigation demands [85].

Enhancing public awareness regarding biochar technology could significantly improve its acceptance and application as a soil amendment. As consumers become more knowledgeable about its environmental and agronomic advantages, there is a compelling opportunity for increased demand and support for biochar in landscaping and gardening practices, ultimately facilitating its broader adoption within urban green spaces. The multidimensional benefits of biochar in agriculture and the environment are shown in Figure 4.

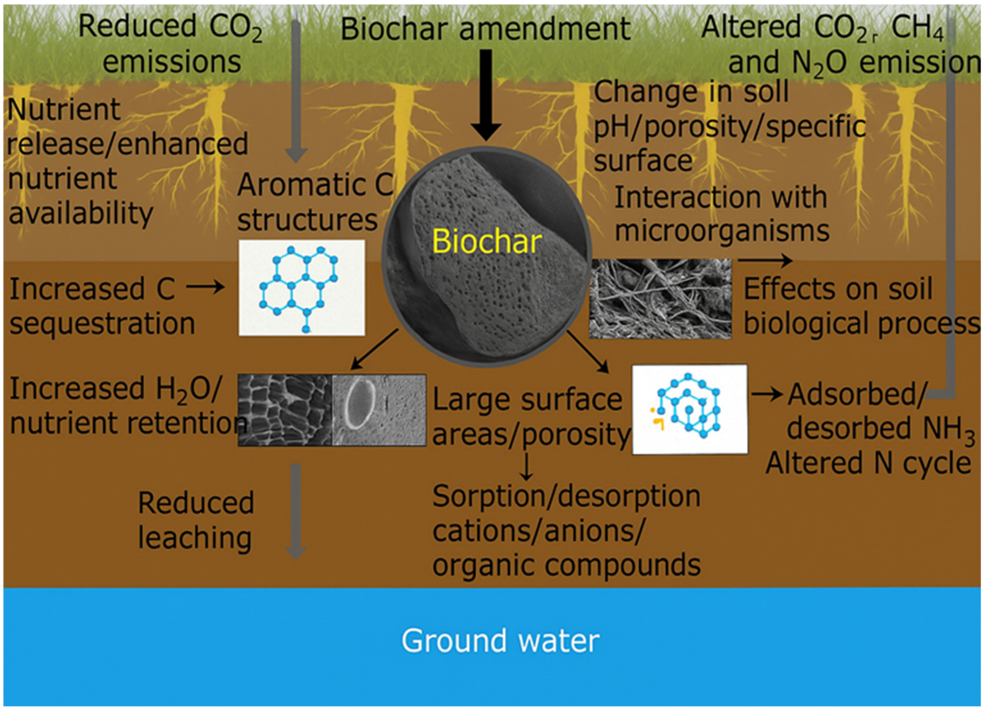


**Figure 4.** Multidimensional benefits of biochar in agriculture and the environment (Irfan et al., 2017) [21].

*5.2. Biochar-Based Solutions for Stormwater Management*

In urban environments worldwide, stormwater runoff frequently goes untreated, leading to the accumulation of diverse contaminants, including heavy metals and pesticides, before they enter aquatic systems. Tackling this environmental issue necessitates innovative solutions, with biochar emerging as a promising candidate. The ongoing trend of urbanization is contributing to a rise in impermeable surfaces, which threatens aquatic ecosystems and highlights the urgent need for effective mitigation strategies. This urban growth alters hydrological dynamics, causing increased runoff peaks, larger volumes of runoff, and reduced time-to-peak flows [51].

These modifications to the hydrological cycle significantly impact water resource management, exacerbating challenges such as heightened flood risks, diminished water availability, and declines in water quality. Biochar-based filtration is increasingly recognized as a best management practice (BMP) for stormwater treatment, noted for its efficacy in contaminant removal. As a porous by-product of bioenergy production, biochar presents a sustainable and cost-effective alternative to traditional activated carbon. Various pilot and full-scale systems, particularly in the Pacific Northwest, have successfully utilized biochar in diverse filtration configurations [86,87].

Research from Oregon State University has indicated that biochar media blends can achieve over 95% removal rates for dissolved and total copper and zinc across varying stormwater samples. To optimize performance, these blends were engineered with additional components to enhance biological activity, buffer pH levels, and improve hydraulic flow. Critical design factors include the variability in biochar types, appropriate media blending, and postprocessing practices to ensure stable hydraulic performance.

Numerous studies have highlighted the benefits of integrating biochar into stormwater management media. These advantages encompass improved soil water retention, enhanced aggregation in fine-textured soils—thereby increasing infiltration rates—and augmented fertility in nutrient-deficient soils, ultimately facilitating plant growth [88]. Biochar also plays a crucial role in filtering heavy metals and mitigating the transport of harmful bacteria, such as *E. coli*, into local waterways.

The multifaceted advantages of biochar in stormwater treatment are rooted in its ability to adsorb pollutants, retain soil moisture, release nutrients gradually for plant uptake, enhance soil fertility, and foster beneficial plant microbiota [51]. It effectively removes organic contaminants such as herbicides, insecticides, oils, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and flame retardants through various sorption mechanisms [79].

Further research has systematically assessed the impact of varying biochar content on the hydrological performance of green roofs using both experimental approaches and numerical simulations [1]. Soil columns containing 0%, 5%, 10%, and 15% biochar were subjected to artificial rainfall, allowing for the derivation of hydraulic parameters through inverse modeling techniques. Simulations further evaluated rainwater management during actual rainfall events. Findings reveal that, while biochar increases saturated water content, it leads to a reduction in saturated hydraulic conductivity. Specifically, a 10% biochar content yielded optimal results in rainwater management, facilitating the greatest reduction in peak flow and longest delay in outflow, whereas a 5% biochar content produced the most significant reduction in runoff and peak flow delays. These insights are invaluable for optimizing biochar application in urban rainwater management strategies.

### *5.3. Integrating Biochar into Green Roof Systems*

In recent years, green roofs have emerged as a promising intervention for urban stormwater management, optimizing limited spatial resources while contributing to both climate change adaptation and mitigation strategies. The performance of green roofs is heavily influenced by the properties of the chosen growth medium [51]. Traditional substrates often fall short of the specific needs of these applications, making biochar a compelling alternative due to its unique benefits.

A comparative analysis of two modular green roofs—one equipped with a commercial substrate and the other integrating biochar—was conducted under controlled simulated rainfall events (ranging from 10 to 80 mm) [88]. This study focused on runoff retention and water quality metrics. Results indicated that both substrates achieved similar runoff retention rates near 72%. Over time, there were observed declines in total nitrogen (TN), total phosphorus (TP), chemical oxygen demand (COD), and iron (Fe). Notably, despite comparable average runoff concentrations of most pollutants, the biochar substrate demonstrated enhanced pH buffering capacity and significantly lower TN and COD levels. Specifically, the concentrations of TN and COD from the commercial substrate were approximately double those from the biochar substrate. These findings underscore biochar's efficacy in reducing pollution loads and its potential role in mitigating urban non-point-source pollution through green roofs.

Furthermore, a study investigating the incorporation of sewage sludge biochar into the soil, enhanced with various plant types at application rates of 0–20% [89], highlighted biochar's capacity to improve moisture retention, temperature regulation, microbial diversity, and plant growth. An optimal application rate of 10–15% yielded substantial enhancements in microbial and plant biomass, with increases reaching 89.6% and 54.2%, respectively. These improvements can be attributed to the superior soil conditions and heightened microbial activity associated with biochar integration.

In summary, the incorporation of biochar into green roof substrates offers a valuable strategy for reducing urban non-point-source pollution while also enhancing plant water use efficiency, a critical aspect of water conservation in green roofing systems. Tailoring biochar applications to meet specific rainwater management objectives can further amplify the ecological advantages of these systems.

### *5.4. Biochar as a Sustainable Insulation Material*

Biochar, a porous and carbon-dense material, has emerged as a promising thermal insulating solution for building applications due to its inherently low thermal conductivity and high porosity [90–92]. These properties position biochar as a viable candidate for enhancing energy efficiency in the built environment by effectively minimizing thermal losses [93].

Recent investigations have shown that the incorporation of latent heat storage biocomposites (LHSBCs) into construction materials can markedly elevate building energy efficiency [94]. These biocomposites are synthesized through the vacuum impregnation of biochar with bio-based fatty acid phase change materials (PCMs). Biochar is selected primarily for its environmental benefits, while the PCMs offer low depletion risks. Experimental findings indicate that LHSBCs exhibit stable thermal properties, with a thermal conductivity measured at 0.1727 W/mK, paralleling that of gypsum board. Although there is a slight decrement in latent heat capacity compared to pure PCMs, numerical simulations reveal that LHSBCs have the potential to reduce annual building energy consumption by 531.31 kWh, underscoring their promise as a sustainable material for energy-efficient construction.

The low thermal conductivity of biochar not only serves as an effective insulating medium but also aids in maintaining lower indoor temperatures during warmer months and conserves heat during colder periods [93]. This attribute significantly diminishes heating and cooling requirements, thereby improving the overall energy efficiency of buildings [95]. Current research efforts are focused on developing an innovative biocomposite that merges biochar with natural inorganic clay (NIC) to explore its applicability and efficacy as a sustainable building material.

Beyond its insulation properties, biochar offers additional benefits when integrated into wall systems. Its ability to regulate moisture plays a crucial role in mold prevention and enhancing indoor air quality, while its high porosity contributes to effective sound insulation. For example, studies have illustrated that the inclusion of biochar sourced from dried distillers' grains into concrete systems can markedly enhance sound absorption capabilities, particularly within the 200–2000 Hz frequency range, by facilitating the formation of internal pore networks [94].

## 6. Biochar Production from Urban Forests: A Sustainable Opportunity for U.S. Cities

Woody biomass represents an underutilized resource, increasingly available due to ongoing urbanization and the rising frequency of disturbance events, which improve biomass availability for various applications, including biochar production. In the U.S., urban forests encompass approximately 141 million acres [50]. Notably, around 60 National Forests and Grasslands lie in close proximity to urban centers with populations exceeding one million, characterizing them as urban national forests. By broadening the access criteria to individuals residing within 80 km of these national forests, an additional 153 million persons would gain access to urban forests [17–19].

Estimates indicate that potential losses of urban woody biomass could approach 46 million tons of fresh-weight merchantable wood—translating to about 1.7 billion cubic meters of lumber or 16 million cords of firewood, assuming an annual mortality rate of 2% [96]. The economic valuation of urban wood waste in the U.S. is projected to range between USD 89 million and USD 786 million, contingent on the products derived, such as wood chips or lumber [97]. This urban wood waste can be repurposed into commercial lumber or transformed into secondary products, including furniture, flooring, and pallets. Alternatively, it serves as a feedstock for bioenergy generation and biochar production.

Urban forest biomass encompasses fresh-cut wood residues generated from tree removals and maintenance, emerging as a promising feedstock for biochar synthesis [98]. For instance, Boulder, Colorado, is piloting a community-scale bioenergy–biochar system developed by TrollWorks, capable of converting approximately 200 tons of biomass into 30 tons of biochar annually, yielding 15% while cogenerating 200,000 Btu of heat per hour. If scaled, up to 45 such units could process the city's urban tree waste, potentially generating about 1356 tons of biochar from municipal forest residues. Establishing a biochar market could yield numerous benefits, including reduced disposal costs, diversion of organic waste from landfills, and long-term carbon sequestration.

In Minneapolis, Minnesota, an accumulation of wood waste—specifically logs and tree limbs resulting from damage inflicted by the emerald ash borer (EAB) on local ash populations—poses a significant challenge [98]. To address this issue, Hennepin County is investigating sustainable alternatives, with biochar emerging as a viable solution for converting urban forest biomass into a regenerative resource that presents both economic and environmental advantages. A proposed pilot biochar production unit in Minneapolis is designed to process 16 tons of green wood daily, producing roughly 4 tons of biochar per day, with an annual processing capacity of 3200 tons of green biomass depending on operational conditions. This unit aims to utilize biomass from tree removals executed by the Park Board, potentially generating around 1120 tons of biochar annually from the Park Board's 4481 metric tons of wood biomass, exclusive of contributions from private tree care initiatives (Table 1).

Producing biochar from urban forest biomass represents a critical opportunity to enhance carbon sequestration by optimizing the management of woody biomass. In the United States, urban forests are estimated to sequester approximately 834 million metric tons of carbon, corresponding to around 1.67 billion metric tons of dry-weight tree biomass. However, these forests face an annual biomass loss of 2 to 7% due to tree mortality [97].

To effectively harness carbon sequestration potential, it is essential to implement strategies that manage urban vegetation carbon stocks, thereby improving carbon assimilation rates while mitigating carbon losses. Essential strategies include developing comprehensive vegetation management plans, executing robust tree planting initiatives, instituting thorough tree care programs to lower mortality rates, and creating conditions favorable to the growth of old-growth trees. An integral part of this strategy is the production of biochar from low- and no-value woody residues, which not only optimizes biomass utilization but also generates heat and energy. This dual approach could empower cities to increase carbon sequestration capacities and transition toward carbon-neutral or carbon-negative energy systems, contributing to the development of sustainable urban ecosystems. Moreover, the application of biochar is anticipated to enhance urban soil health, while also presenting additional market opportunities, such as its incorporation into cement and asphalt products [99].

For municipalities seeking sustainable wood waste management, biochar production emerges as a viable alternative to conventional disposal methods. Traditional practices like chipping, natural decomposition, and open burning swiftly release sequestered carbon into the atmosphere, exacerbating greenhouse gas emissions and climate change. In contrast, pyrolysis—the thermal decomposition of biomass in an oxygen-restricted environment—facilitates the transformation of organic materials into stable biochar. This process not only captures and stabilizes carbon but significantly curtails greenhouse gas emissions during biomass conversion.

Recent evaluations indicate that utilizing biomass for biochar in Boulder, Colorado, may yield significant carbon mitigation benefits, with reductions in $CO_2$ emissions projected between 400 and 2053 metric tons annually https://carbonneutralcities.org/wp-content/uploads/2023/02/Boulder-Strategy.pdf (accessed on 14 April 2025)..

This assessment is timely, as the city explores the feasibility of large-scale biochar production initiatives. By adopting biochar technology, municipalities can effectively tackle wood waste management challenges while making substantial contributions to their overall carbon footprint reduction and advancing environmental sustainability.

**Table 1.** Available urban tree biomass and biochar production potential in 2 case study cities [98].

| City | Available Urban Tree Biomass (MT Annual) | Production Technology Assumptions | Estimated Biochar Production Potential (MT Annual) |
| --- | --- | --- | --- |
| Boulder, USA | 9041 tons | Community-scale TrollWorks system | 1356 tons |
| Minneapolis, USA | 4481 tons (city tree removals)<br>56,148 tons (county wood waste) | 2-line ARTi reactor | 1120 tons (city biomass)<br>14,037 tons (county-wide) |

### *6.1. Case Study: GHG Life Cycle Assessment of CharBoss® Biochar Production and Potential Use for Carbon Dioxide Removal (CDR) Certificate Generation*

As illustrated in Figure 1, the CharBoss is an advanced mobile biochar production system specifically engineered to function in tandem with air curtain burners [100]. This state-of-the-art technology originated from a Cooperative Research and Development Agreement (CRADA) between Air Burners and the U.S. Forest Service. The CharBoss is strategically designed to enable forest managers to efficiently eliminate undesired biomass while generating biochar—a valuable soil amendment produced through combustion.

A comprehensive life cycle assessment (LCA) was conducted in accordance with International Standards Organization (ISO) protocols to evaluate the carbon capture capabilities of the CharBoss® air curtain burner developed by Air Burners Inc., Palm City, FL, USA. This in-depth analysis focused on the device's ability to convert waste biomass, resulting from forest fire mitigation initiatives, into biochar for the enhancement of forest soils. The primary objective was to determine the net greenhouse gas (GHG) emissions and quantify the potential for issuing carbon dioxide removal (CDR) certificates, particularly in accordance with the Puro.earth methodology.

The LCA meticulously scrutinized each phase of the process, from the initial biomass collection to the final biochar application, employing empirical data garnered from U.S. Forest Service operations. The findings were significant, revealing a net removal of approximately −2.70 metric tons of $CO_2$ equivalent (MT $CO_2$eq) per ton of biochar produced. Annually, the CharBoss system can yield an impressive 2403.81 MT $CO_2$eq in marketable CDR certificates. This proof-of-concept study not only highlights the CharBoss's critical role in wildfire management but also emphasizes its potential as a scalable and sustainable biochar production solution, creating a unique avenue for revenue through verified carbon credits.

### *6.2. Opportunity Assessment*

To thoroughly assess the viability of a biomass–biochar system, it is essential to evaluate the feedstock waste stream [1]. Leveraging tree inventory data through a top-down approach, combined with bottom-up surveys from arboricultural firms, can yield invaluable insights into the volume and composition of wood waste available for biochar production.

Furthermore, an analysis of the current dynamics of woody biomass within urban environments—including its pathways to organic recycling facilities, landfills, or other disposal routes—provides a foundational understanding necessary to evaluate the net carbon implications of redirecting wood waste towards pyrolysis systems.

Implementing a proof-of-concept is paramount to demonstrating the potential impacts of biochar and testing its feasibility prior to larger-scale investments. Given the variability in biochar properties and their targeted applications, evaluating outcomes from localized pilot projects is crucial for accurately assessing their economic, environmental, and social ramifications. For instance, investigating biochar's efficacy in enhancing water retention within turf management can facilitate its wider adoption [100]. Similarly, analyzing biochar's application in roadside settings for pollutant remediation may reveal benefits for local and state agencies, potentially leading to its integration into roadway management frameworks and design guidelines.

### *6.3. Case Study: Hiawatha Avenue*

In the fall of 2019, Hennepin County collaborated with the City of Minneapolis to launch a comprehensive stormwater management initiative along Hiawatha Avenue, focusing on enhancing both rainwater infiltration and the ecological integrity of local vegetation. The grass median had suffered from significant soil compaction and invasive weed infestation, warranting a targeted soil restoration strategy.

To tackle this issue, the project team systematically stripped away the existing soil, replacing it with a nutrient-dense mixture of compost and hardwood biochar at a ratio of 1:9. This formulation was specifically engineered to optimize both soil structure and fertility, thoroughly incorporating it into the upper 6 inches of the median's profile. The compost utilized was sourced from the SMSC Organics Recycling Facility, recognized for its high-quality organic inputs, while the hardwood biochar was included to improve moisture retention and enhance microbial activity within the soil matrix.

In conjunction with the soil amendments, an engineered swale was constructed to facilitate effective stormwater conveyance and promote natural infiltration patterns. Following this, a specialized pollinator lawn mix, rich in native flowering species, was meticulously sown and covered with burlap. This layer served as an erosion control measure while also aiding in moisture retention to promote robust seedling establishment.

To bolster the project's ecological outcomes, forty mature trees were strategically replaced in the area, utilizing a custom 50–50 backfill mix of biochar and compost. This innovative backfilling method aimed to enhance tree survival rates and support vigorous growth and resilience in the new plantings. Collectively, these efforts contribute to the restoration of the local ecosystem, fostering a healthier environment for both wildlife and community residents.

## 7. Conclusions

The exploitation of woody biomass derived from urban tree waste offers substantial avenues for generating diverse bioproducts, such as biochar, bioenergy, compost, lumber, and wood chips. These processes are critical for mitigating both national and global warming impacts while reducing the risk of eutrophication, particularly when juxtaposed with conventional landfill disposal of organic materials.

Urban soils frequently face challenges in supporting a variety of tree species due to factors like contamination, compaction, and nutrient deficits. However, the application of biochar—an engineered carbon product obtained through the pyrolysis of biomass—can considerably improve tree vitality and overall soil productivity. Biochar enhances soil morphology, augments water retention, and boosts nutrient availability, thereby fortifying the resilience of urban forests. By synergizing urban tree planting initiatives with locally sourced biochar, communities can reduce maintenance costs and enhance carbon sequestration within the soil.

Moreover, the establishment of green infrastructure—including urban forests, parks, and green roofs—yields numerous benefits that transcend mere aesthetic improvements. This infrastructure bolsters both human and animal health, fosters biodiversity, and plays a pivotal role in carbon sequestration efforts. Capitalizing on woody biomass from urban and suburban regions for bioproducts addresses dual issues: mitigating wildfire hazards and bolstering soil quality to sustain tree growth and ecosystem services, which include enhanced air quality and habitat provision.

Advancements in data collection methodologies and technology empower urban areas to accurately assess the available volumes of woody biomass, leading to informed predictions regarding bioproduct yield and market needs. While small green spaces, such as community parks, may exert limited influence on carbon sequestration, expanding these initiatives across urban landscapes can significantly reduce the urban carbon footprint. To harness this potential, it is imperative to implement a comprehensive suite of policies that govern the scale and efficacy of biomass conversion methods.

Recognizing biochar as a stable carbon product suitable for soil amendment offers a viable alternative to the landfill of woody biomass, adopting a more integrative strategy for managing dead biomass. Although still an emerging practice, the production and utilization of urban biochar can be markedly accelerated by establishing long-term research goals. Creating a collaborative network of cities dedicated to biochar initiatives would facilitate the aggregation of extensive datasets, promoting in-depth investigations into ecological, hydrological, and soil-specific responses to biochar applications. This cooperative approach could elucidate the benefits of carbon storage and sequestration, thereby informing urban biomass management policies and practices.

The following conclusions highlight the potential of utilizing urban woody biomass for biochar production and its relevance in sustainable urban management across the USA:

I. Urban woody biomass constitutes a significant, yet largely untapped, resource with considerable potential for sustainable biochar production and carbon sequestration.
II. Cities like Boulder and Minneapolis exemplify the technical and economic viability of converting urban tree waste into biochar, effectively diminishing waste while enhancing soil and environmental health.
III. Biochar production systems such as CharBoss® can efficiently process both forest and urban biomass, offering scalable carbon removal solutions backed by verified life cycle assessments.
IV. The integration of biochar into urban forestry and stormwater management projects, illustrated by Minneapolis' Hiawatha Avenue initiative, demonstrates multifaceted advantages, including improved soil structure and increased water retention.
V. The creation of regional biochar markets can facilitate the diversion of organic waste from landfills, mitigate greenhouse gas emissions, and foster the development of carbon-negative urban infrastructure.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| BC | Biochar |
| BMP | Best Management Practice |
| Btu | British Thermal Unit |
| CEC | Cation Exchange Capacity |
| $CH_4$ | Methane |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| COD | Chemical Oxygen Demand |
| EAB | Emerald Ash Borer |
| GHG | Greenhouse Gas |
| GSI | Green Stormwater Infrastructure |
| HHV | Higher Heating Value |
| IBI | International Biochar Initiative |
| LHSBC | Latent Heat Storage Biocomposite |
| NIC | Natural Inorganic Clay |
| $NO_2$ | Nitrogen Dioxide |
| $O_3$ | Ozone |
| PAHs | Polycyclic Aromatic Hydrocarbons |
| PCBs | Polychlorinated Biphenyls |
| pH | Potential of Hydrogen |
| $PM_{10}$ | Particulate Matter < 10 μm |
| SEM | Scanning Electron Microscope |
| SMSC | Shakopee Mdewakanton Sioux Community |
| $SO_2$ | Sulfur Dioxide |
| SSA | Specific Surface Area |
| TN | Total Nitrogen |
| TP | Total Phosphorus |
| UHI | Urban Heat Island |
| U.S. | United States |
| VOCs | Volatile Organic Compounds |
| WC | Wood Chips |

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