Biochar Use In Stormwater Management

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Executive Summary

Stormwater is the runoff from rain, snow, or ice. Runoff from the built and natural environments alike are often contaminated with pollutants including sediment, heavy metals, petroleum-based hydrocarbons, nutrients, herbicides, insecticides, pesticides, flame retardants, plastic additives and micro-plastics, chlorides, bacteria and oxygen-demanding organic matter. Over the last decade biochar, a long-lasting form of carbon made from organic materials, has begun to play an ever-expanding role in managing and decontaminating stormwater. This report outlines where and how it can be used effectively, as well as providing an overview of the market potential for biochar producers.

Biochar has been used commercially in stormwater management in the US for more than ten years to bring public and private storm water management systems into compliance with regulatory permits. Use has grown as more trials are being conducted and biochar's benefits and value proposition are better understood. One of the most publicized projects is from Stockholm, Sweden where biochar is used extensively since initially being piloted in 2009 to reduce runoff and revitalize tree plantings. In the US, Minnesota has published specifications for biochar use in stormwater management and the City of Minneapolis has begun instituting city wide programs after visiting Stockholm and learning from the project managers there. Other US municipalities are also exploring biochar in urban stormwater management projects.

Biochar is the product of heating organic feedstocks[1] in a low oxygen environment, through a process called pyrolysis creating a stable, carbon-rich form of charcoal. Biochar can be used in many applications where activated carbon is currently used to remove substances from either water or gaseous streams. Activated carbon is often made from mined carbon sources such as peat and coal, but can also be made from renewable organics including dense coconut shells., Biochar, on the other hand, is made from a wide variety of organic (i.e., renewable) sources. Like conventionally activated carbon, pyrolyzed woody biomass can also be activated to similarly increase its available surface area.

Biochar can be a cost-effective filtration solution where organic and inorganic substances, as well as some microbial constituents, need to be removed. Research and experience has proven biochar to be useful in a variety of applications which makes it an attractive additive for stormwater treatment as a filtration and water treatment media. It is also used in soil restoration and remediation, constructed wetlands, green roofs, and water treatment.

Stormwater treatment in the US is driven by the 1972 Clean Water Act, a federal law administered by state and local agencies[2]. For biochar producers, the market potential will be significant once biochar is specified and approved for stormwater projects[3]. How big might the market potential be? Using the City of Chicago as an example—with an impervious surface area of about 105,000 acres— in 2020, bids were requested for over $250M of stormwater treatment projects. A 10% biochar inclusion rate on those projects is estimated to require roughly 100,000 cubic yards of biochar. To put this singular case in perspective, Chicago represents about 4% in area of the 10 largest US cities by population which cover 3900 sq. miles or 2.5 M acres.

The first section of this report provides relevant information for stormwater filtration project managers and designers. It provides a synopsis of biochar's potential for stormwater treatment and a short tutorial of biochar's relevant characteristics for treating stormwater or effluent. The following two sections provide commercial examples of biochar used in stormwater treatment projects and field trials, as well as a sampling of related research of biochar's use in stormwater treatment. The last section offers biochar producers insight on how to serve the stormwater treatment sector effectively.

[1] Biochar feedstocks are largely woody or crop residues , but could include bones, manure, livestock litter, and other inputs to create specialized chars.

[2] This is the founding regulation, but the main drivers now are the NPDES, MS4 and TMDL regulations. Also see Sections 1 and 4.

[3] Most public agencies require materials to be named in specifications (e.g Stormwater Manual). The specifications are made by licensed engineers and the approved materials are listed publicly, then purchased and applied by approved contractors.

Introduction and Overview

Stormwater is the runoff from rain, snow, or ice. Urban stormwater is often contaminated with a number of pollutants including sediment, heavy metals, petroleum-based hydrocarbons, nutrients, herbicides, insecticides, pesticides, PAHs[4], PCB[5]s, flame retardants, plastic additives and micro-plastics, chlorides, bacteria and oxygen-demanding organic matter. The problems associated with runoff from the built environment, like erosion, sedimentation, and flushing excess nutrients and chemicals dominate treatment projects and will be the focus in this report.

Biochar is the product of heating organic feedstocks[6] in a no to low oxygen environment, to create a very stable, carbon-rich form of charcoal. One of the primary differences between the term charcoal and biochar, is that biochar is intended to be used in ways the prevent the carbon from converting back into CO2 (as charcoal does when burned). Carbon preserving uses within the stormwater context include its use in ponds, streams, erosion control and reduction of runoff from impervious surfaces (e.g., roads, parking lots, etc.) Increasingly biochar is being used in a variety of applications where activated carbon (AC) has traditionally been used such as water or gaseous filtration. Where activated carbon is made from peat, coal, and organics including dense coconut shells or wood; biochar is made from organic (i.e., renewable) sources exclusively. Like conventionally activated carbon, biochar can also be activated to further expand its surface area with additional processing.

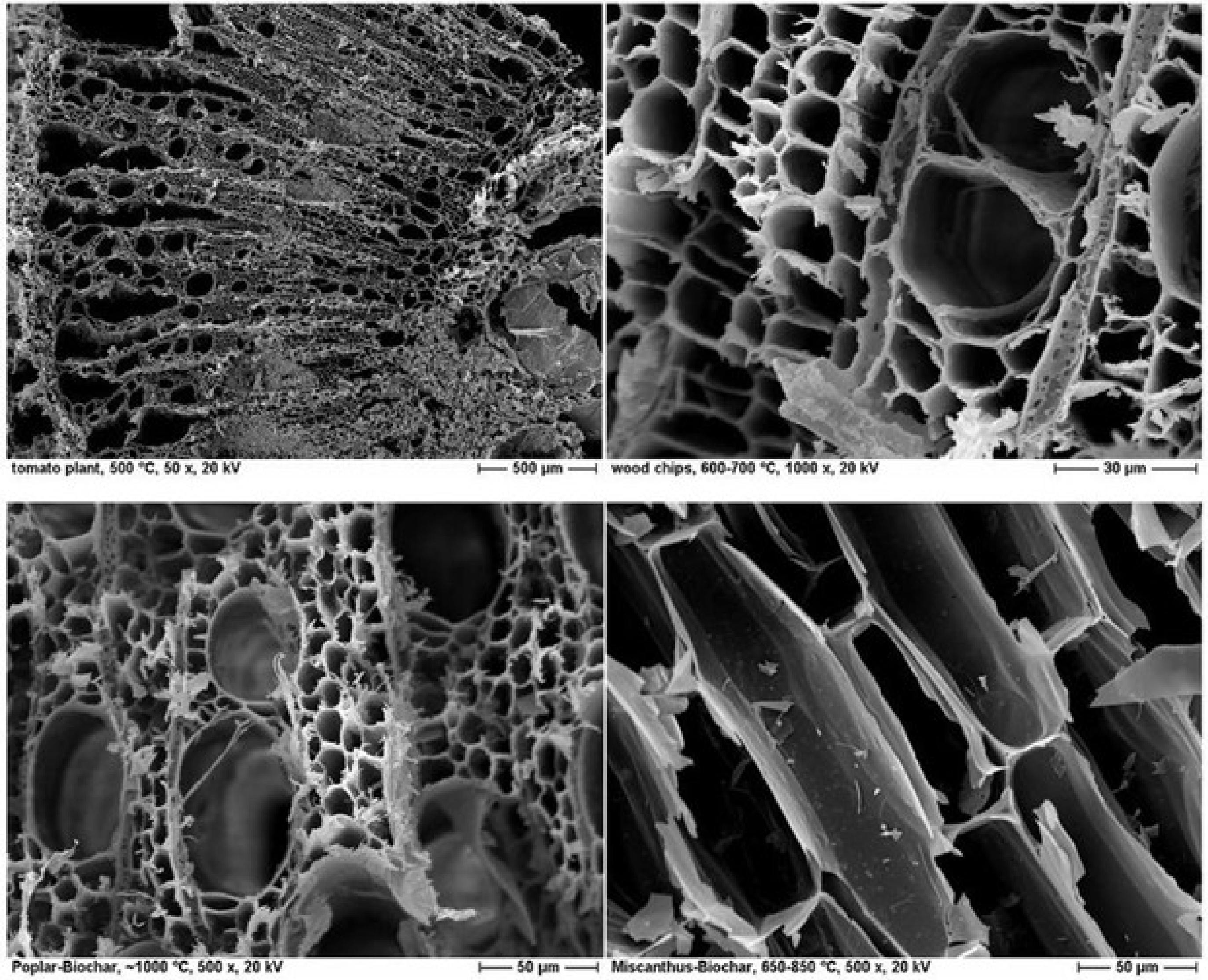
Biochar can be a cost-effective option to replace activated carbon in many filtration applications and its production likely has a much smaller carbon footprint. Activated carbon costs between $1000 and $5000/Ton[7] and has surface areas of 500 to 3,000 meters2 per gram 4, versus biochar's cost from $800 to $2000 per ton with surface areas of 200 to 600 m2/g[8].

The significance of biochar's surface area formed by a long-lasting[9] matrix of almost pure carbon can be seen in Figure 1. The porosity and surface area of biochar provide multiple benefits. The porosity and surface area properties make biochar suitable for absorption and chemical adsorption. The biochar surfaces also support biofilm formation and habitats for beneficial organisms. These properties illustrate why biochar can be an advantageous candidate for filtration applications.

A more detailed look at biochar's characteristics is included in Section 1. Each section of this report has been written to stand-alone, with practical stormwater management applications presented in Section 2 and highlighted research in Section 3. Section 4 is an introduction to the stormwater management market for producers primarily.

[4]Polycyclic Aromatic Hydrocarbons
[5]Polychlorinated Biphenyls
[6]Biochar feedstocks are largely woody or grassy (cellulosic), but could include bones, manure, livestock litters, and other inputs to create specialized chars.
[7]Comparison is on a weight basis because activated carbon and biochar can differ significantly in bulk density.
[8]**The Properties of Fresh and Aged Biochar**; S Joseph, P Taylor, F Rezende, K Draper, A Cowie; The Properties of Fresh and Aged Biochar
[9]Biochar is considered a stable carbon product for decades to millennia.

Figure 1. Biochar production and application supply chain (adapted from: Anderson et al. 2017. Chapter 2 in Biochar: A Regional Supply Chain Approach in View of Climate Change Mitigation, Cambridge University Press.)



Glaser, B, Wiedner, K., Biochar-Fungi Interactions in Soils; February 2013; DOI: 10.1201/b14585-4

Section 1.

Biochar for Stormwater Management Designers and Project Managers

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Biochar can help projects meet National Pollutant Discharge Elimination System (NPDES)[10] permit requirements in stormwater applications by addressing:

- filtration of metals (Zn, Cd, Cu)
- filtration for bacteria (E coli)
- filtration for algae (biofilm mechanism)
- filtration of organics and inorganic
- filtration of nutrients

These capabilities of biochar can be used specifically to aid in:

- improved functionality of Best Management Practices (BMPs)
- green infrastructure including green roof substrate admixture
- urban soil restoration
- improving establishment of vegetation for stormwater and erosion control
- enhancement to nature-based solutions (streams, floodplains, reforestation)

Biochar is available in bulk, delivered via walking floor trailer or in super sacks. It can be applied by mixing with conventional aggregates or by layering it; some examples of applications:

- in soil and engineered media blends for stormwater treatment "structures" such as filters, vaults, rain gardens, structured soils, bioretention pits, green roofs, and infiltration containments
    - o Biochar's particle size distribution can be specified to achieve a desired soil/media texture
- in filter bags (e.g. "socks") around construction, roadwork, in ditches, etc.
- in hydroseeding mixes for its water retention ability, to aid in the establishment of grasses which will reduce runoff and increase infiltration

Bulk biochar costs have been relatively stable at $200 per cubic yard (CY) in supersacks (additional cost for transportation/ delivery.) The cost per ton ranges from about $800 to $2500 with an estimated 10 CY/dry ton. Conventional equipment can be used to move, handle, and incorporate the biochar; however, the same precautions should be taken for any biochar fines as for similar dusty materials. Treatment rates used in recent in-soil and certain engineered media applications have been in the range of 2-4% by mass or 7-15% by volume[11].

[10] Stormwater treatment is governed by the National Pollutant Discharge Elimination System (NPDES). The NPDES permit program addresses water pollution by regulating point sources that discharge pollutants to waters of the United States. Created in 1972 by the Clean Water Act, the NPDES permit program is authorized to state governments by EPA to perform many permitting, administrative, and enforcement aspects of the program. For additional discussion, see Section 4.

[11] Ranges used in recent projects and recommend from research.

The developing carbon credit market will have a significant effect on the economics of biochar use with payments for carbon offsets and reductions on qualifying projects.

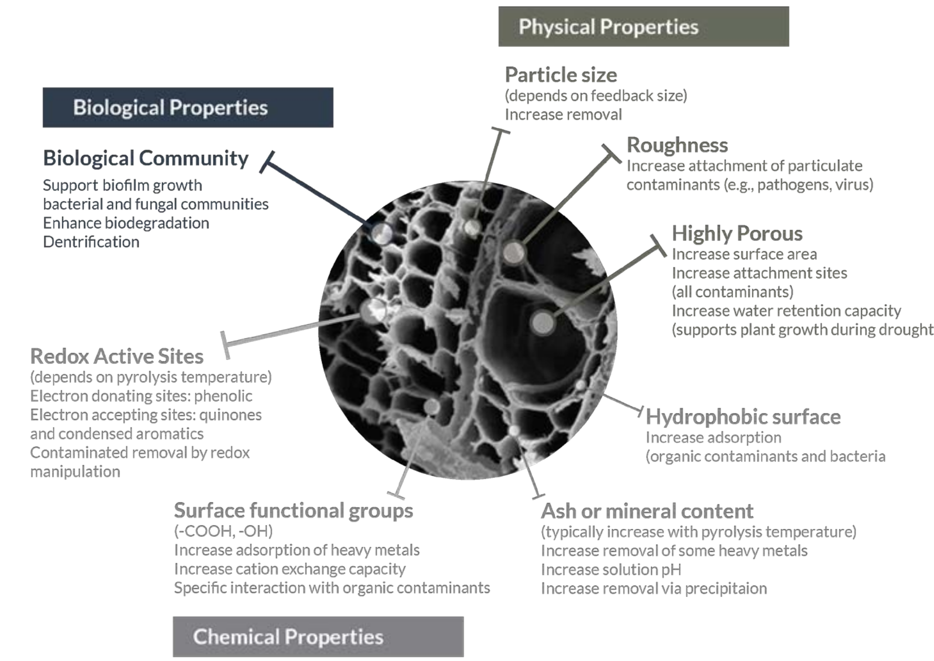
There are clear advantages for project managers to market their "greening" efforts by using biochar while taking advantage of the opportunity to profit from the long-term sequestration of carbon. This is especially true for high-volume users and for permanent installations. Carbon markets are becoming more established as a climate change mitigation strategy and biochar is an established practice with evaluation criteria in place. Current brokers of biochar derived carbon credits in the US are Verra[12] and Puro,[13] but other systems (like CarbonFuture[14] and Climate Action Reserve[15]) are coming online with biochar protocols, so researching this financial avenue is advisable, especially since some systems place the credits with the producer and others with the end user.

Understanding Biochar

The first step in considering or specifying biochar is to understand the relevant characteristics of biochar that impact sorption efficiency such as surface area, particle size and porosity. Not all biochars are the same; they are highly variable when it comes to physical, chemical, biological and electrical properties. Commercially available biochars can be evaluated by looking at lab test results.

A good general reference for biochar testing standards and biochar properties is available at the International Biochar Initiative (IBI) website[16]; its focus is for use in soils, with an emphasis on safety and sequestration. The best current resource for stormwater managers is a 2018 review of research on potential applications of biochar for stormwater management[17]. Figure 2 is taken from that publication to highlight the aspects of biochar specification for stormwater management. Figure 3 illustrates biochar characteristics with relevance to filtration which are common reference points in a broad range of applications.

Figure 2. Physical, chemical, and biological properties of biochar for removal of contaminants from stormwater.



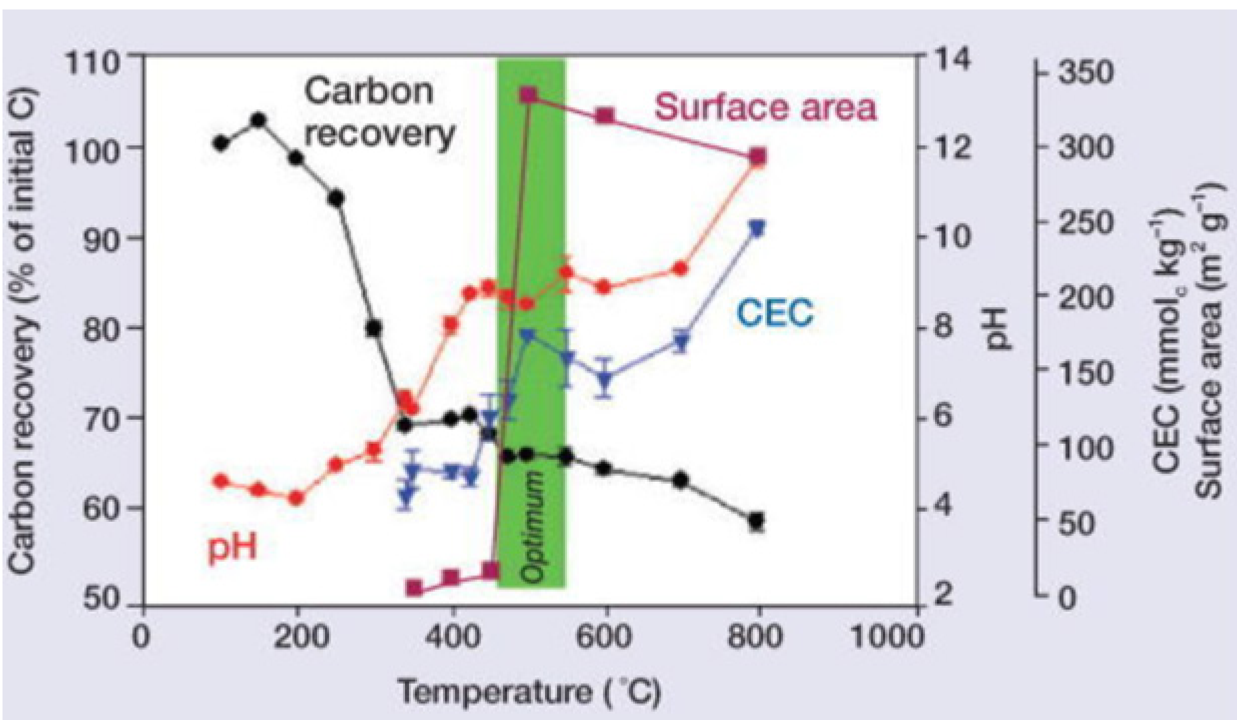
Plenty of room for carbon on the ground: Potential applications of biochar for stormwater treatment; Mohanty et al.; 2018; Science of the Total Environment 625

Regardless of the application, the biochar feedstock must be safe. There can be no toxic residues, so the feedstock used to make the biochar has to be a "pure" organic substance like woody material (wood chips, green waste, and Class A C&D wood would qualify, but not treated or contaminated debris), grasses, manure/litter chars, or clean agricultural residues.

Using Figure 3 to better understand biochar properties, a biochar made above 450°C will provide desirable characteristics—not too much liming effect, good CEC (cation exchange capacity), decent surface area expansion, and acceptable carbon recovery. To be certain of the characteristics, a lab analysis is essential—either provided by the producer or, ideally, from an independent lab. The carbon recovery line deserves further explanation: the pyrolyzed carbon comes in two forms: stable (also referred to as recalcitrant) and labile (or reactive). The stable carbon fraction will remain in the soil for a long time (decades to millennia). The labile fraction will react with other elements in the soil and ultimately convert to CO2 within a few years. The higher temperature chars (with the most surface area) tend to have higher proportions of stable carbon. This is an important consideration for project planning, but also if carbon credits are being sought.

The graph for Figure 3 is for a specific hardwood, and the graphs of other hardwoods would be similar. However, a biochar derived from softwood will look slightly different, but grass or manure-based biochars will differ significantly.[18] Getting input from a knowledgeable resource is advisable and the US Biochar Initiative's site[19] is a good resource for finding suppliers and consultants.

Figure 3. Biochar Characteristics



Lehmann, J. (2007), Bio-energy in the black. Frontiers in Ecology and the Environment, 5: 381-387. https://doi.org/10.1890/1540-9295(2007)5[381:BITB]2.0.CO;2

[12]Verra, voluntary carbon market projects: https://verra.org/voluntary-carbon-markets/

[13]Puro Earth, carbon removal marketplace: https://puro.earth/

[14]CarbonFuture.earth, a CO2 platform: (carbonfuture.earth)

[15]Climate Action Reserve, California and Voluntary carbon market registry; https://www.climateactionreserve.org/

[16]International Biochar Initiative; Resources: https://biochar-international.org/resources/

[17]Plenty of room for carbon on the ground: Potential applications of biochar for stormwater treatment; (Mohanty et al.; Science of the Total Environment 625 (2018) 1644–1658; https://www.renanvalenca.com/files/review.pdf

[18]Analyses of biochar properties; Allaire SE, Lange SF, Auclair IK, Quinche M, Greffard L; (2015); CRMR-2015-SA-5. Centre de Recherche sur les Matériaux Renouvelables, Université Laval, Québec, Canada

[19]US Biochar Initiative; Directory: Directory by State | US Biochar Initiative (biochar-us.org)

Summary

The addition of biochar in stormwater management projects offers designers and project managers multiple benefits. Besides "greening" the project by using a renewably sourced carbon-rich media, the biochar offers increased water retention over conventional materials. It may also provide additional benefits in porosity management and improved or accelerated growth of cover plants when in a soil-mix substrate. Biochars are readily available, cost competitive, and have the capacity to remove a wide range of stormwater pollutants in conditions expected during intermittent infiltration of stormwater.

Section 2.

Experiences using Biochar for Stormwater Treatment

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This section explores recent field trials and experiences of various stormwater projects using biochar. A few demonstration projects are presented here with more detailed information available from the links provided.

1. A highly publicized project from Stockholm, Sweden began with a test installation of structural soils using biochar plus structural aggregates designed to improve the vitality and lifespan of trees planted along streets. An unanticipated benefit which has since become widely publicized and replicated was the structed soils impact on improving stormwater management. This biochar pilot project began in 2009 and was sufficiently successful in reducing tree mortality that it inspired the City to adopt the design for widespread use and to establish biochar production with combined heat and power generation within the City of Stockholm and now in various other cities within Sweden. The project also resulted in the city being awarded a €1M Mayors Challenge award from the Bloomberg Philanthropies to expand their biochar production and utilization. Below are details about the initial tree/stormwater management pilot project from a Biochar Journal article evaluating the project[20] and introducing the subsequent award for community-based biochar production.

> *"Urban trees face various challenges which frequently lead to high tree mortality, shorter lifespans and increased maintenance cost. To improve tree health and survivability, Stockholm has been testing and refining the use of structured soils and biochar for nearly 10 years. These structured soils consist of gravel mixed [originally] with smaller soil amendments such as peat, sand, clay, lava and more [recently] with…biochar. In some cases, 6-year-old trees planted in structured soils with biochar were five times larger than 30-year-old trees planted using more traditional urban tree planting techniques.*
>
> *Although they don't yet have scientific data to quantify the impact, anecdotal observations of improved storm water filtration have been observed. The pavement is… designed to collect rainwater from roofs, sidewalks, and streets and transport it to a concrete inlet near the tree. This inlet not only serves as a water reservoir for the tree but also proved very beneficial in terms of storm water management.*
>
> *The Stockholm Biochar Project[21] uses park and garden waste to produce biochar and renewable energy. With the help of the city residents and local authorities, garden and park waste are collected and stored in different waste management centers located across Stockholm. This waste is turned into biochar through a carbonization process. The by-product of the biochar production, pyrolysis gas, generates energy for the city's district heating system. The five [biochar facilities] are expected to produce 7,000 tons of biochar by 2020, sequestering 25,200 tons of CO2 (the equivalent of taking 3,500 cars off the road) and producing corresponding 25,200 MW/hour of energy (the equivalent of heat for 400 apartments). Within eight years, the project will deliver a revenue on the city's investment estimated approximately over 854,000 EUR."*

2. The City of Minneapolis, Minnesota, USA has been inspired by the Stockholm successes with biochar[22] and the City's Environmental Services Supervisor, Jim Doten[23], has led the effort to incorporate biochar in a number of projects[24]. From a 2019 article by Bloomberg Cities17, the importance of the Stockholm project is highlighted in Minneapolis' adoption of biochar as a climate friendly product for use in the city:

> *"The Minneapolis team visited the tidy plant in Stockholm's public-works yard, where the city turns tree limbs into biochar — and simultaneously kicks off energy to heat buildings. And they went to one of the new super-sustainable neighborhoods Stockholm is known for, where biochar helps sponge up and filter stormwater while helping street trees thrive.*

[20]Planting Urban Trees with Biochar; Embren B, the Biochar Journal 2016; Arbaz, Switzerland. ISSN 2297-1114; www.biochar-journal.org/en/ct/77

[21]City of Stockholm Biochar Project: Stockholm Biochar Project | Nordregio and Digital Tour of Stockholm Biochar Facility - YouTube

[22]Minneapolis City Bloomberg biochar connection: https://bloombergcities.medium.com/inspired-by-stockholms-success-a-u-s-city-goes-big-on-biochar-70e011ccf865

> *Visitors heard a lot about the various properties of biochar that make it so useful in a municipal context. When mixed into soil, biochar helps retain nutrients and moisture, enabling urban farmers, foresters, and landscapers to grow stronger, healthier plants that can resist drought. Along streets and roadways, it can help hold and filter stormwater, helping to prevent floods and reduce water pollution. Finally, biochar sequesters carbon in the ground, making its use one of the rare "carbon negative" climate strategies cities have at their disposal."*

A 2020 article[25] about the University of Minnesota's Duluth Natural Resources Research Institute's collaboration with the City of Minneapolis' biochar projects noted the City's history and continued efforts:

> *"Minneapolis started using biochar to improve soil health in 2014. Recent projects include a 5-year study with the University of Minnesota to test biochar's impact on tree growth and biochar compost in a road median landscaping project on Highway 55. This summer, 15 boulevards in the Tangletown neighborhood are being planted with pollinators in a biochar compost and biochar will be used in rain gardens to filter stormwater. Doten calculated that the Minneapolis biochar program can save as much greenhouse gas emissions as thousands of acres of forest."*

Jim Doten is quoted:

> *"We've seen biochar restore boulevard trees that are stressed from road salt, improve soils impacted by pesticide and herbicide use, filter E. coli and PFAS contaminants," said Doten. "You first hear about it and think, maybe its snake oil, but it works."*

3. A Chesapeake Bay (Maryland, USA) watershed collaboration between the Center for Watershed Protection and consulting engineer Chuck Hegberg[26] resulted in a biochar project which included short term monitoring[27]. It was located on two parcels in Maryland—one installation managing runoff from a ~1½ acre parking lot and another managing a 52 acre residential area. Both bioretention basins were installed with relatively low levels of biochar (~2% by volume) and showed inconclusive response to reducing Phosphorus in the runoff; however, there was little P in the inlet flow to begin with. At both sites, biochar additions were effective at reducing runoff volumes however, the biochar enhancement didn't show a conclusive difference from the control at that inclusion level.

> The final project report noted: *"Both practices [installations] were effective at providing runoff reduction across a wide range of storm events. This result suggests that, for the observed conditions, the runoff reduction effects of stormwater filtering systems are more important than the ability to filter phosphorus." It should be noted that subsequent work with biochar uses higher levels of biochar (10%+) for an effective improvement in stormwater management.*

4. A one-acre retention control project installed by Metzler Forest Products of Reedsville, Pennsylvania, USA consisted of four versions of fill (three plus a control) with a combination of soil, compost, and biochar. This project was highlighted in a Penn State Extension article[28].

> *In a 2021 update on the status of the installation, it was observed that the biochar enhanced cell had denser plant growth than the control and compost-soil cells.*

5. Additional case studies are available from biochar suppliers and consultants. Two examples are:

a. Myles Gray of Geosyntec presented two stormwater projects at the 2016 Biochar Conference. Both projects (in Port Townsend, WA, and Kitsap County, WA) showed successful removal of copper, zinc, phosphorus, and nitrogen compounds. The presentation is available from the conference host: US Biochar Initiative[29].

b. The biochar supplier Stormwater Biochar provides three case studies[30] of successful projects using biochar to mitigate heavy metals and reduce turbidity and biological oxygen demand.

[23]USBI spotlight on Jim Doten: Meet a Biochar Practitioner - Jim Doten, City of Minneapolis | US Biochar Initiative (biochar-us.org)

[24]Minneapolis Biochar Program: https://www2.minneapolismn.gov/government/programs-initiatives/environmental-programs/biochar/

[25]University of Minnesota's Natural Resource Research Institute; Minnesota a leader in biochar research and demonstration

[26]Center for Watershed Protection: https://www.cwp.org/ and reGENESIS Consulting Services, LLC, 256 Frederick Street, Hanover, PA, 17331, USA

[27]Christianson, R., D. Caraco, B. Seipp. 2018. Phosphorus Removal with Hydraulic Control and Biochar Addition to Infiltration Media. Final Report for NFWF Grant #0602.14.044992/44992. Center for Watershed Protection, Inc.

[28]University of Pennsylvania Biochar Enhanced Infiltration Basin in Central Pennsylvania

[29]Myles Presentation at USBI Conference: https://biochar-us.org/sites/default/files/presentations/4.2.3 Gray%2C Myles.pdf

[30]Stormwaterbiochar.com: http://stormwaterbiochar.com/resources/casestudies/

Section 3.

Resources and Research Supporting Biochar Use for Stormwater Treatment

Section 3. Resources and Research Supporting Biochar Use for Stormwater Treatment

An increasing body of research has demonstrated the usefulness of biochar in a variety of applications which make it an attractive addition for stormwater treatment as a filtration and water treatment media. What follows is a sampling of resources for the application and use of biochar for stormwater treatment as well as research pertinent to specific biochar benefits in stormwater management and filtration.

The following articles highlight research which support benefits of biochar used for stormwater treatment. Specific focuses include:

- Resources for the use of biochar in stormwater treatment: 1
- Biochar characteristics beneficial for stormwater management: 1, 2, 3, 4, 6
- Remediation: 4
- Constructed Wetlands: 5
- Green Roof Application: 7
- Activated, Enhanced, or Engineered Biochar: 9
- Bioretention: 2, 3, 6, 8

1. A resource with comprehensive details about biochar and its applicability in stormwater treatment is available in the Biochar and applications of biochar in stormwater management[31] section of Minnesota's Stormwater Manual. It includes discussion of physical and chemical details of biochars as well as selection criteria for various applications. This resource is provided as a model stormwater manual section to permit the use of biochar in projects.

2. The positive impacts of the use of biochar for roadside drainage was demonstrated by the University of Delaware in a project funded by the Transportation Research Board. The project report[32] concluded:

> *"Thus, biochar amendment increased the ability of the tilled roadway soil to reduce stormwater runoff volume and peak flow rate by ~ 50%. This is 2 to 3 times more significant than what might be expected from lab and pilot-scale experiments [also performed as part of this project.]" And: "In summary, biochar amendment to three representative roadway soils indicated that biochar amendment will have beneficial effects on soil hydraulic properties. Experiments at the pilot and field scale demonstrate that these effects enhance stormwater treatment, resulting in reductions in stormwater runoff volume and peak flow rate. Somewhat surprisingly, the benefits of biochar amendment were most pronounced at the field scale, which was attributed to time-dependent formation of soil aggregates that was not yet a significant process at the pilot scale. Using costs determined from field-scale implementation, 0.12 acres of biochar-amendment is needed to treat 1-acre impervious with approximately 83% removal of nutrients and sediments at a cost of ~ $31,700 per impervious acre treated. While these costs are similar to an urban grass buffer ($26,600 per impervious acre), biochar-amendment requires a dramatically smaller footprint: 0.12 versus 3.7 acre per impervious acre for biochar and urban grass buffer, respectively."*

[31]Minnesota Stormwater Manual; Biochar specific section: Biochar and applications of biochar in stormwater management - Minnesota Stormwater Manual (state.mn.us)

[32]Reducing Stormwater Runoff and Pollutant Loading with Biochar Addition to Highway Greenways; P. Imhoff, S. Nakhli; Final Report for NCHRP IDEA Project 182; Oct 2017; https://onlinepubs.trb.org/onlinepubs/IDEA/FinalReports/Highway/NCHRP182_Final_Report.pdf

3. Especially for stormwater treatment projects where the biochar is incorporated with soils, this 2019 report[33] provides insight to the characteristics of biochar, how different manufacturing and processing parameters affect them, and the resultant performance which can be expected.

> *One of the objectives…was to determine the effect of feedstock and preparation conditions such as pyrolysis temperature, retention time, gas flowrate, additives on the biochar characteristics and application potentials. … relevant modification or activation technologies have been discussed for the improvement of the biochar functions. The application of biochar could adjust the soil structure (surface area, pore size and distribution etc.), improve the soil physicochemical properties (pH, cation exchange capacity, water retention capacity etc.) and enhance the uptake of soil nutrients for plant growth; In addition, it also can be used to adsorb various contaminants (heavy metals, organic matters),modify the habit and function of microorganism and mitigate climate problem by changing the bioavailability of elements (C, N, K etc.) in soil. These results also provided the possibility to expend the application of biochar to modify the degraded soils in the saline-alkali soil and industrial regions, further increase the usable area of cultivated land.*

4. Cited earlier15 in the Introduction and Figure 2, the 2018 review of research on biochar used for stormwater management summarized:

> *"Biochar has high potential to remove stormwater contaminants and maintain plant health in stormwater treatment systems. In comparison to activated carbon, use of biochar in stormwater biofilter is particularly viable because of its lowcost and diverse environmental benefits. Based on biochar use at different sections of biofilters, biochar can serve multiple functions:*

- Soil amendment for plant growth, which can substitute the use of other organic amendments such as compost that have negative impact on contaminant leaching.
- Filter media for contaminant attachment/removal. Biochar is particularly useful to remove organic contaminants from stormwater, whereas removal of metals/metalloids, nutrients, and pathogensvaries by a wide range based on biochar surface properties, contaminant properties, and water chemistry.
- Storage media to increase water holding capacity. Increase in saturation by biochar addition can help increase denitrification.
- Redox control agent to further enhance contaminant removal via reduction/oxidation."

[33]Review of Biochar for the Management of Contaminated Soil: Preparation, Application and Prospect; P. Yuan, J. Wang, Y. Pan, B. Shena, C. Wub; Science of the Total Environment 659 (2019) 473–490; doi.org/10.1016/j.scitotenv.2018.12.400

5. For constructed wetlands used in a stormwater management context:

a. A review of biochar used in constructed wetlands and biofilters[34] looked at biochar as: "a versatile and green carbonaceous biomaterial produced by carbonization of various biomasses, has recently been amended into constructed wetlands (CWs) or biofilters (BFs) as a novel alternative substrate for wastewater treatment. In this paper, the performance of biochar amendment in CWs/biofilters with respect to the removal of nitrogen, phosphorus, organic contaminants, heavy metals and pathogens and its concurrent ecological benefits in improving macrophyte growth and mitigating greenhouse gas (GHG) emissions are summarized and evaluated."

b. An amended biochar was tested in a New Zealand constructed wetland with these results:[35]

"This study conducted over 7 months clearly shows that an enriched biochar is a suitable substrate for P removal and retention. N retention was also demonstrated however the study did not specifically look at N reduction in the wastewater because wetlands are generally efficient in removal of N through microbial activity. The efficiency for removal of PO4-P was considerably greater than for the control wetland, the latter exhibiting a diminishing removal rate towards the end of the monitoring period. By contrast, the enriched biochar substrate continued to remove and retain P, verified by elemental and surface analyses. The spent biochar could also be used as a fertilizer for soil enhancement and could have the potential to be regenerated and reused…"

6. Another review of research[36] about biochar used in stormwater treatment found:

> *Biochar has been increasingly used as a filter medium in engineered low impact development systems (e.g., bioretention systems) for decontamination of urban stormwater and management of hydrology. This review paper critically analyzes the performance of biochar-based biofiltration systems for removal of chemical and microbial pollutants present in urban runoff. Biochar-amended biofiltration systems efficiently remove diverse pollutants such as total nitrogen (32 – 61%), total phosphorus: (45 – 94%), heavy metals (27 – 100%), organics (54 – 100%) and microbial pollutants (log10 removal: 0.78 – 4.23) from urban runoff. The variation of biofiltration performance is due to changes in biochar characteristics, the abundance of dissolved organic matter and/or stormwater chemistry. The dominant mechanisms responsible for removal of chemical pollutants are sorption, ion exchange and/or biotransformation, whereas filtration/straining is the major mechanism for bacteria removal."*

7. For biochar used in green roof installations this publication[37] provides information useful in the design of other stormwater applications such as bioretention ponds, drainage swales, and constructed wetlands.

> Depending on the design objective of the green roof, different biochar amendment types are preferable. With the aim of improving plant function, reducing system weight and maintaining hydrological performance, amendment with coarse biochar fractions is preferable in geographical locations with high rainfall intensities. Furthermore, air-filled porosity and infiltration capacity for these mixes are consistent with widely accepted industry guidelines. Conversely, if the design objective for a green roof primarily aims to increase stormwater retention, then greater water holding capacity (WHC) is beneficial and can be achieved by amending green roof substrates with finer biochar fractions [≤2mm]. However, fine biochar fractions reduce infiltration, even at lower amendment rates, which necessitates additional stormwater precautions (i.e. appropriately dimensioned overflows) in geographical locations where probable maximum rain intensities exceed the infiltration capacity of these mixes.

[34]Application of biochar as an innovative substrate in constructed wetlands/biofilters for wastewater treatment: Performance and ecological benefits; S. Deng, J. Chen, J. Chang; Journal of Cleaner Production, Volume 293, 15 April 2021, 126156; https://doi.org/10.1016/j.jclepro.2021.126156

[35]Phosphorus Adsorption onto an Enriched Biochar Substrate in Constructed Wetlands Treating Wastewater; L. Boltona, S. Joseph, M. Greenway, S. Donne, P. Munroe, C. Marjo; Ecological Engineering: X 1 (2019); doi.org/10.1016/j.ecoena.2019.100005.

[36]Biochar-based Bioretention Systems for Removal of Chemical and Microbial Pollutants from Stormwater: A Critical Review; BK. Biswal, K. Vijayaraghavan, D. Tsen-Tieng, R. Balasubramanian; Journal of Hazardous Materials 422 (2021) 126886; doi.org/10.1016/j.jhazmat.2021.126886

[37]Biochar Particle Size and Amendment Rate are More Important for Water Retention and Weight of Green Roof Substrates than Differences in Feedstock Type; J. Werdin, R. Conn, T. Fletcher, J. Rayner, N. Williams, C. Farrell; Ecological Engineering 171 (2021) 106391; doi.org/10.1016/j.ecoleng.2021.106391

[38]The full report is accessible at: Biochar Enhanced Infiltration Basin in Central Pennsylvania

8. A case study of a **BIOCHAR ENHANCED INFILTRATION BASIN IN CENTRAL PENNSYLVANIA**[38] by Penn State Extension was published in 2021 and details the design and installation of a stormwater control system. The installation was installed by Metzler Forest Products using their own biochar. Some of the conclusions were:

> This project shows that installing a biochar enhanced infiltration basin is similar to installing a traditional infiltration basin. For the most part, Metzler was able to install the basin with their regular machinery and equipment. Adaptations to storage space for the biochar and super sacks to store the product in before mixing are new issues that arise. The experience of installing this biochar enhanced infiltration basin has shown that using biochar in stormwater BMPs is feasible to achieve. However, it's important to note that many types of biochar are available on the market, and it may be necessary to consult scientists and engineers with biochar experience before installing projects like this to ensure the appropriate biochar is used

9. Considering biochar as an activated carbon replacement, this research report[39] about Activated Biochar offers insight about a potentially cost-effective water treatment option.

> Despite relatively low surface areas (200–600 m2/g), the steam-activated biochars were highly suitable adsorbents for the chemical species tested as well as for microplastics removal. The results indicate that ultra-high porosities are not necessary for satisfactory water purification, supporting the economic feasibility of bio-based adsorbent production.

Low-Cost Biochar Adsorbents for Water Purification Including Microplastics Removal; V. Siipola, S. Pflugmacher, H. Romar, L. Wendling, P. Koukkari; Appl. Sci. 2020, 10, 788; doi:10.3390/app10030788; www.mdpi.com/journal/applsci

Section 4.

For Biochar Producers:

Market Potential for Biochar use in Stormwater Management

Section 4. For Biochar Producers:Market Potential for Biochar use in Stormwater Management

Biochar producers looking to serve the stormwater treatment industry will need to consider a very different clientele than those in the agricultural domains. Where agricultural uses are largely unregulated, stormwater treatment is highly regulated for both point and non-point sources.

Stormwater treatment in the US is governed by the National Pollutant Discharge Elimination System (NPDES). The NPDES permit program addresses water pollution by regulating point sources that discharge pollutants to waters of the United States. Created in 1972 by the Clean Water Act, the NPDES permit program is authorized to state governments by the Environmental Protection Agency (EPA) to perform many permitting, administrative, and enforcement aspects of the program.

The 1987 amendments to the Clean Water Act, commonly referred to as the Water Quality Act of 1987, address non-point source pollution associated with stormwater runoff. The EPA defined urban stormwater (previously considered a non-point source) as a point source with numerous physical locations (or points) of discharge. This permit program is called Municipal Separate Storm Sewer System (MS4). The objective of the MS4 program is to maintain and benefit water quality in creeks, streams, and waterways by reducing pollutants in stormwater runoff.

While states are allowed to manage their own projects via the NPDES, there are often state and local level requirements which must also be considered. To effectively serve this market, one needs to understand the system. Briefly, these are the typical steps involved in stormwater projects:

1. The customer, such as an agency or company, will specify the project's scope to comply with an NPDES permit and will forward this to their staff or contract a consultant.
2. Civil engineers design the project's details and specify the materials needed, at which point they let bids for a contract.
3. A contractor will purchase the materials, including the biochar and apply it as specified by the Engineer.

Specifications for pilot or test projects may be written on a case-by-case basis, but need to be specified as an acceptable material in the governing regulations or the technical manual issued by the governing agency for the design and installation of stormwater management projects.

Potential buyers of biochar for stormwater projects include:

- Government agencies: public works, facilities management, departments of transportation, and organizations with oversight for water quality.
- Engineering firms: particularly those conducting projects requiring compliance with regulations for water quality, such as housing developments, commercial or industrial construction.
- Erosion control and stormwater installation contractors
- Other businesses could include point-source operations needing to control discharge such as: compost operations, confined animal operations, sawmills and log yards, biomass power plants, wastewater treatment plants or petroleum distribution terminals.

There is significant competition for what materials used for stormwater projects, especially for aggregates which constitute most of the fill used. However, biochar can enhance the performance of most aggregates based on pilot projects and extensive research. Initial cost competitiveness may be a hurdle which will make demonstrating the holistic payback critical however, the Transportation Highway Board project detailed in article 2 of Section 2[40] notes that that biochar is useful in places where there is a small available footprint.

Market Assessment Details:

Stormwater includes the runoff from rain, snow, or ice. The applications for which biochar can be used include ponds, streams, and runoff from impervious surfaces (paved areas and buildings.) The problems associated with runoff from the built environment dominate treatment projects and are the focus of this market assessment.

The Economic Research Service of the USDA estimates impervious area covers 60 million acres[41] in the US, or roughly an area the size of Oregon. It is estimated that two-thirds of the cover is pavements and one-third is building roofs. The most effective treatment strategies are where flows are lower, before the water converges into high volume streams. This is illustrated well by retention ponds installed near roadways, parking lots, highway interchanges, etc. to allow the runoff to seep slowly into the ground. The BMP Guide presented in the textbox below illustrates the best practices of installing treatments at or near their source.

The following summary of stormwater treatment options is from the City of Chicago's BMP Guide[42]. An estimate of 1/3:2/3 surface area is split between roof and paved area which translates to about 45,000 acres of building roofs and 105,000 acres of pavement. Green roofs can benefit from the lighter weight of biochar as compared to other green roof substrates such as topsoil or compost. Shallow rooted plants can benefit from biochar's ability to enhance water and nutrient retention. Biochar can be used as part of the treatment in all the other practices to varying extents—from a few percent of the aggregates to 100% in filtration media.

- *Green Roof - "Green" roofs are layers of living vegetation installed on top of buildings*
  - *Applicability: In both new building designs and rehab opportunities, the load-bearing capacity of the roof may dictate the most appropriate type of system. Green roofs are appropriate in most of the properties in the City including residential, commercial, industrial and institutional properties.*
- *Downspouts, Rain Barrels and Cisterns - the City of Chicago encourages the careful disconnection of downspouts so that roof runoff can flow directly into vegetated areas. There are several options for doing this: • Runoff can be sheeted across the lawn (see "filter strip" discussion). • Runoff can be routed via a surface swale into a rain garden or onsite detention or retention facility (see separate discussions of these approaches). • Runoff can be temporarily stored in rain barrels or cisterns.*

[40] Reducing Stormwater Runoff and Pollutant Loading with Biochar Addition to Highway Greenways; P. Imhoff, S. Nakhli; Final Report for NCHRP IDEA Project 182; Oct 2017

[41] USDA land use data: https://portal.nifa.usda.gov/web/crisprojectpages/0406455-land-use-in-the-united-states.html

[42] Chicago Stormwater Guide: guideToStormwaterBMP.pdf (chicago.gov) Note that states and municipalities have stormwater technical manuals or guides which detail the required elements and approved materials for the project.

o Applicability: Effective downspout disconnection requires that there be adequate landscaping or vegetation available to accept the water. Rain barrels are appropriate where vegetation is limited, provided that the collected water can overflow to open green space areas. Diversion and/or storage of roof runoff with rain barrels or cisterns is applicable to most residential, commercial and institutional properties in the City.

- *Permeable Paving - Permeable paving refers to paving materials – typically concrete, stone or plastic – that promote absorption of rain and snowmelt. The discussion that follows focuses primarily on one form of permeable pavement – paving blocks and grids, as they are the most common and available type of permeable paving. These modular systems contain openings that are filled with sand and/or soil.*

  o Applicability: Permeable paving is particularly appropriate for the following applications: overflow and special event parking, driveways, utility and access roads, emergency access lanes, fire lanes and alleys

- *Natural Landscaping- Natural landscaping refers to the use of native vegetation – particularly prairie, wetland and woodland species – on a development or redevelopment site. Native vegetation is a low-cost alternative to traditional landscaping that utilizes turf grass and ornamental plantings.*

  o Applicability: Natural landscaping is feasible on nearly all sites as an alternative to conventional landscaping. It should be tailored to individual site characteristics, factoring in topography, soils, drainage patterns and sun exposure.

- *Filter Strips- Filter strips are vegetated areas that are designed to receive runoff from adjacent impervious surfaces.*

  o Applicability: Roof runoff and parking lot runoff can be distributed over the width of lawn areas to promote absorption and filtering. Filter strips are strongly recommended in buffer zones between developed areas and sensitive aquatic environments. They are particularly appropriate as buffers for land uses that generate high pollutant loads, such as roadways and parking lots, and are useful in controlling erosion and sediment wash off during construction. Filter strips are probably most appropriate on developments where there are significant expanses of pervious areas (green spaces) adjacent to impervious surfaces (such as parking lots). Specifically, they may be used in the following applications: residential (roof runoff), commercial (roof and parking lot runoff) and vegetated buffers (adjacent to stream or wetland areas)

- *Bioinfiltration: Rain Gardens - Bioinfiltration systems are shallow, landscaped depressions used to promote absorption and infiltration of stormwater runoff.*

  o Bioinfiltration is suitable for developments that have sufficient room for the water to be absorbed. Suggested applications include: parking lot islands, residential developments utilizing swale drainage for pre-treatment, commercial developments utilizing filter strips adjacent to parking lots for pre-treatment, and campus developments utilizing swale drainage and filter strips for B pre-treatment.

- *Drainage Swales- A swale is a broad, vegetated channel used for the movement and temporary storage of runoff. In contrast to conventional curb-and-gutter/storm sewer systems, swales can reduce both the rate and volume of stormwater runoff on a site.*

  o Applicability: Drainage swales are applicable on virtually all development sites. In dense urban settings swales generally will be used in conjunction with storm sewers, rather that in lieu of storm sewers. Suggested applications include: office campus, commercial, industrial, multi-family residential, parking lots, residential parkways and highway drainage (where right-of-way widths are adequate). One type of swale is a depressed median – a recessed, landscaped area within paved surfaces. Depressed medians can be used as an alternative to raised parking lot islands, allowing water to flow into them from the surrounding pavement. Using vegetation is important in order to filter contaminants that may enter the median from the surrounding pavement.

- *Naturalized Detention Basins- Conventional detention is designed to prevent flooding by temporarily storing stormwater runoff and releasing it gradually to the downstream drainage system. Naturalized detention is intended to serve multiple functions, in addition to flood prevention, including pollutant removal and creation of wildlife habitat (where appropriate). Natural detention basin designs emulate natural lake or wetland systems by utilizing native plants along the water's edge and on side slopes. The design generally incorporates flat slopes at the edge of the water or wetland, shallow zones of emergent vegetation at the edge of wet basins, and a combination of vegetated and open water areas in wetland basins.*

  o Applicability: Natural detention basin designs are suitable for all development types. Detention may not be feasible on very small sites – such as individual lots

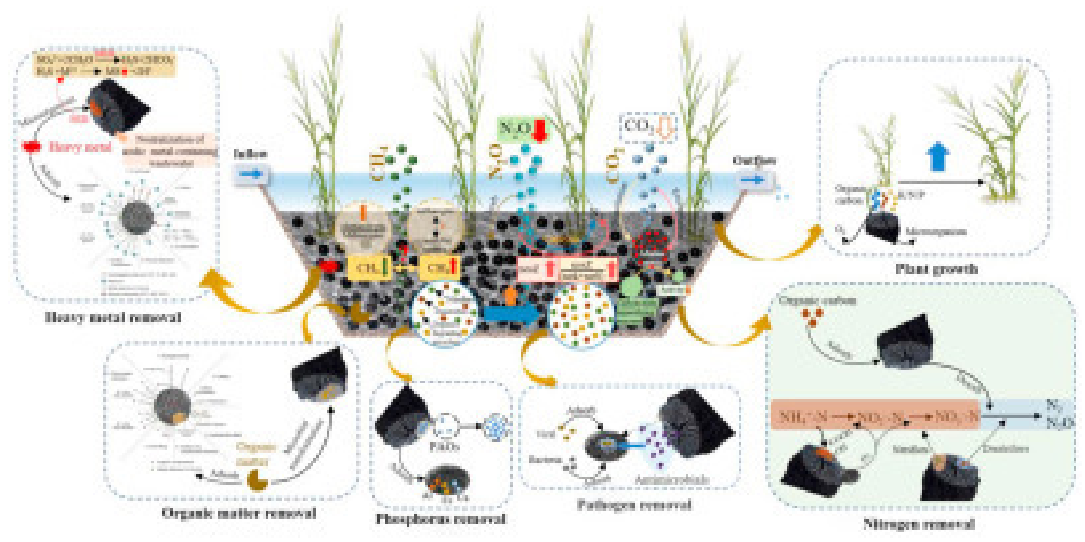
Table 1. Summary of Chicago Stormwater BMPs

BMP	Typical Initial Cost	Percentage Reduction in Water Volume or Pollutants *
Green Roof Extensive Intensive	 $8-12/sq.ft. $15-25/sq.ft.	Cadmium, copper & lead: 95% reduction Zinc: 16% reduction Captures and stores run-off from small to moderate storms.
Rain Barrel	$20-150 each	Captures and stores runoff from small to moderate storms.
Permeable paving	2-3 times conventional costs	Reduces quantity of surface runoff from small to moderate storms.
Natural land-scaping	Similar to conventional costs: from $2,000-4,000/acre	Suspended solids & heavy metals (such as cadmium & lead): 80% Nutrients (such as phosphorus & nitrogen): 70% Reduces residential runoff by 65%
Filter strip	Similar to conventional costs	Suspended solids & heavy metals (such as cadmium & lead): 70-90% Nutrients (such as phosphorus & nitrogen) and organics: 25-65%
Rain Garden	$3-4/sq. ft.	Removes runoff and pollutants from small storms.
Bioinfiltration	$10-40/sq.ft.	Best option for reducing surface runoff as well as removing pollutants.
Drainage Swale	Less than conventional costs	Suspended solids: 30-70% removal; nutrients: 10-30% removal. Best at removing runoff in small storms.
Detention Basin	Similar to conventional costs	Reduces stormwater runoff rates and pollutants. Suspended sediments & pollutants: 60-90% removal. Nutrients & organic matter: 40-80% removal.

* Chart figures based on information provided by Northeastern Illinois Planning Commission.
** While some of the initial costs may be higher than conventional costs, many stormwater BMPs pay for themselves via reduced maintenance costs over several years

An important stormwater treatment option not mentioned in the Chicago BMP examples are constructed stormwater wetlands.[43] They are systems designed to maximize the removal of pollutants from stormwater runoff through settling and both uptake and filtering by vegetation. Constructed stormwater wetlands temporarily store runoff in relatively shallow pools that support conditions suitable for the growth of wetland plants. There are two types of constructed wetlands for stormwater runoff treatment: standard wetlands and subsurface gravel wetlands. Figure 4 illustrates the potential for a constructed wetland using biochar.

Figure 4. Constructed wetland/biofilter treatment systems using biochar



Application of biochar as an innovative substrate in constructed wetlands/biofilters for wastewater treatment: Performance and ecological benefits; Deng et al.; Journal of Cleaner Production Volume 293; 15 April 2021, 126156

Market Potential

The market potential for using biochar in stormwater management and treatment is significant. The market for the US stormwater management industry stood at $5.3B in 2020 and expected to grow to over $8B by 2026. Southern states represent the largest segment geographically due to the heavier precipitation and natural disasters which lead to heavy flooding. Primary segments within the industry include urban stormwater management, highway construction, and housing, commercial, and industrial development (the built environment). Municipalities represent one of the largest segments as many cities are facing steep impacts from heavy rain so they are investing in various types of stormwater management infrastructure include the development of swales, bio-retention ponds, and pervious pavement[44].

[43]New Jersey Stormwater Manual Tech Manual_6.2_Cons Wetlands 2_15_11 (njstormwater.org)

[44]United States Stormwater Management Market...; Water and Waste Management, September, 2021; https://www.techsciresearch.com/report/united-states-stormwater-management-market/3715.html

[45]National Land Cover Dataset- includes any built surface-such as roads, sidewalks, parking lots, and rooftops.

To illustrate the potential of the urban markets (as opposed to the much larger metropolitan statistical area or MSA), the City of Chicago will be used as an example:

Urban Chicago covers 234 sq miles. Using EPA's estimate that 70% of urban areas are impervious,[45] there are 164 sq mi; or 104,960 acres producing runoff. For every inch of precipitation, each acre of impervious surface generates 27,000 gallons of runoff which means the City has to manage almost 3 billion gallons of stormwater.

A 1% market penetration on an area basis would require treating 1.64 sq mi. or 1,050 acres. Using a recent stormwater project treatment cost of $250,000 per acre would require a $263M investment. [The City of Chicago had over $250M in stormwater contracts out for bid in 2020.]

If biochar is added at the rate of 10% by volume to a 2500 cubic yards (yard) per acre project (as was done in the Metzler project described in Article 8 of Section 1), 250 yards would be required. At a nominal cost of $200/yard, for the 1050-acre example market, the biochar component would be worth $53M for 26,000 tons of bone dry[46] biochar[47]. Referring again to the Transportation Research Board project by the University of Delaware above, compared to 23 BMPs for stormwater management, the 4% biochar installation's performance "For the same treatment for 1-acre impervious, biochar is less expensive than 20 other BMPs – up to a factor of 10 less."

To put this singular example in perspective: the 10 largest US cities by population cover 3900sq mi or 2.5M acres. The 10 largest metropolitan statistical areas (Table 2) cover 90,300 sq mi or 58M acres[48]. To further put this in perspective, Chicago is the 7th largest in urban area and the 2nd largest MSA in the US

Table 2. 10 Most Populated US Metropolitan Statistical Areas

Metropolitan Statistical Area	Area (Sq Miles)
1. Los Angeles	33,954
2. Chicago	10,856
3. Houston	10,000
4. Dallas-Fort Worth	9,300
5. Washington DC	5,600
6. Philadelphia	5,100
7. Atlanta	8,400
8. New York	4,669
9. Boston	1,422
10. Miami	1,000

[46]Moisture Content Effect: If the bulk density of biochar is 8lbs/ ft3 and water is 62.4lbs/ ft3, there will be 108lbs of water in a 50% moisture content mix per cubic yard. The water component would take up only 1.7 ft3 or 6.3% of the volume. For consistency, biochar-by-volume has been used unless noted.

[47]Calculation details: Biochar is typically 7-9lbs/CF dry; using an 8lbs median yields 216lbs per CY.

[48]US Census Bureau for both urban and Metropolitan Statistical Area data

As a further example of the stormwater market's potential for biochar, the nation's highway system and the built environments are prime candidates with significant treatment needs and broad geographic distribution. Data on biochar use for these markets is not readily available, but the scale of the markets, with their mandated stormwater management component, deserve to be highlighted:

In 2017, there were 4.18 million miles of road in the United States, including Alaska and Hawaii, according to the Federal Highway Administration. The core of the nation's highway system is the 48,254 miles of Interstate Highways, where one four-lane mile of interstate (with paved shoulders and no median) covers roughly ½ acre. $66B is spent annually on upgrade and maintenance. Additionally, there are another 126,568 miles of major roads which comprise the National Highway System. It carries most of the highway freight and traffic in the U.S. Local governments maintain about 77 percent of all roadway miles, state highway agencies are responsible for about 19 percent, and the federal government owns about 4 percent of all roads, mainly in national parks, military bases and Indian reservations.[49] Total spending on highway construction in 2018 was $99.6B and is expected to increase to $103B by 2022[50].

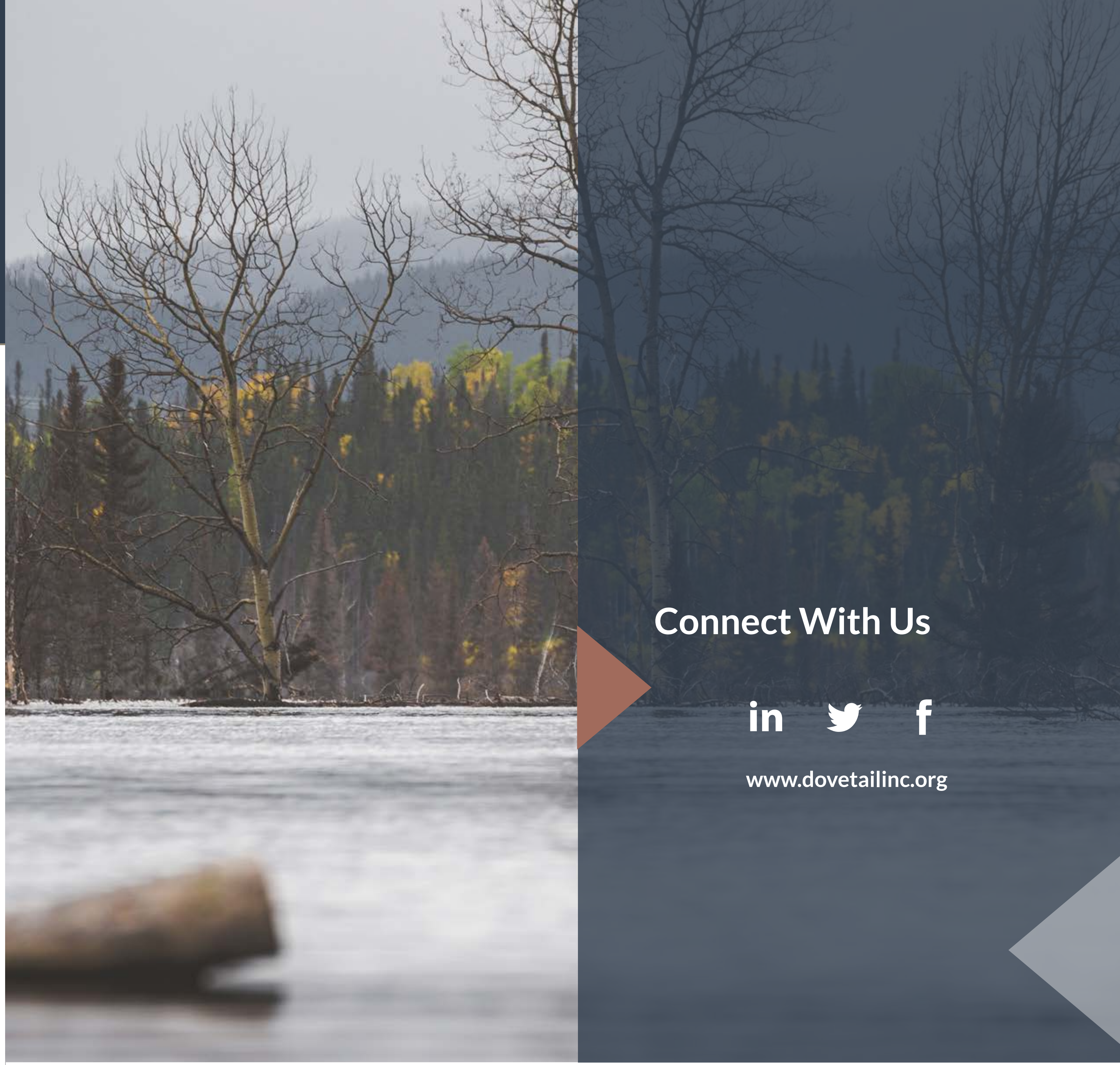
The "Development" Market consists of residential and commercial building and non-structural construction. The estimated US spending for 2021 is $1.5T with most of that concentrated in urban areas. While an estimate of the acreage this development covers is difficult to obtain with accuracy, an assumption that it covers significant acreage seems reasonable and makes it an opportunity for stormwater treatment options in which biochar can play a role. With high-density urban areas creating up to 100% impervious surface area, and with residential areas not uncommonly reaching 40 to 60%, stormwater management is a factor in all construction projects and is an imperative from a permitting standpoint.

Summary:

Biochar used in stormwater management is a huge potential market. There is a need however, for more research and demonstration projects to speed adoption. To successfully penetrate this market biochar producers need to further refine the specifications of both biochar characteristics required for different uses and for their application. Specifically, there is a need for:

- More case studies
- In different regions and for different applications
- Which demonstrate how the biochar was used, how much was used, its benefits, costs, carbon sequestration potential, with an LCA (life cycle analysis) comparison between substrates used, etc.
- Including any follow-up monitoring data or observations, especially if there was a control for comparison
- Research to better understand biochar-based substrates, particularly its capacity for retaining stormwater and contaminants

[49]American Road and Transportation Builders Association FAQ: Frequently Asked Questions - The American Road & Transportation Builders Association (ARTBA)
[50]Statistica Highway construction data: Highway construction in the U.S. - statistics & facts | Statista.



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