BIOCHAR FOR BIORETENTION SYSTEMS

A REVIEW OF BIOCHAR USE IN BIORETENTIONS, BIOFILTERS, AND BIORETENTION SOIL MEDIA

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ACRONYMS & ABBREVIATIONS

Acronym/Abbreviation	Definition
AWC	Available water content
BGB	Below ground biomass
BMP(s)	Best Management Practice(s)
BPA	bisphenol A
BRS	Bioretention System
BSM	Bioretention soil media
bv	By volume
CBw	Chesapeake Bay watershed
CWP	Center for Watershed Protection, Inc.
ETC	Emerging Toxic Contaminants
FC	Field capacity
GI	Green Infrastructure
Ksat	Saturated hydraulic conductivity
MWD	Mean weight diameter
N	Nitrogen
NbS	Nature-based solutions
OPFR	Organophosphate Flame Retardants
P	Phosphorus
PAW	Plant available water
PWP	Plant wilting point
SE	Standard error
STAC	Science and Technical Advisory Committee
TMDL	Total Maximum Daily Load
TOC	Total organic carbon
TOrCs	Trace organic contaminants
TP	Total porosity
TSS	Total suspended solids/sediment
ZVI	Zero-valent iron

Introduction

The STAC Workshop report on Using Carbon to Achieve Chesapeake Bay (and Watershed) Water Quality Goals and Climate Resiliency (Hegberg et al., 2024, p. 47-48) introduces the need and potential for biochar use in urban landscapes (i.e., stormwater) applications as follows:

> The rapid growth of urbanization in the Chesapeake Bay watershed poses an incredibly difficult challenge, if not impossible, to meet the total maximum daily load (TMDL) nitrogen, phosphorous and sediment reduction targets by 2025. However, this rapid urbanization growth exacerbates environmental impacts beyond the TMDL targets, including increased susceptibility to flooding, increasing emerging toxic contaminants (ETCs), decreasing vegetation cover, biodiversity loss and habitat fragmentation, and climate change, such as urban heat island effect increasing human health risks and primarily affecting environmental justice communities (Liao et al., 2023).
>
> Urbanization fundamentally shifts the terrestrial water cycle (precipitation recycling), reduces evapotranspiration, increases the rate and volume of stormwater runoff produced and deteriorates the water quality of the receiving water body, in this case the Chesapeake Bay watershed (Tirpak et al., 2020). Green infrastructure (GI) is the management of stormwater runoff using natural ecosystems or engineered systems that mimic natural systems and have seen increasing deployment in urbanized areas as a nature-based solution (NbS) to mitigate urban environmental impacts (Liao et al., 2023).
>
> GI is a significant tool for many urbanized communities but is expensive to implement and requires long-term operations and maintenance on hundreds, if not thousands of small-scale, Best Management Practices (BMPs). The high cost of urban stormwater BMPs has been a major limiting factor for communities with limited funds and competing priorities, along with site constraints (e.g., poor soils, utilities) that further drive up the cost or make BMPs infeasible. Lack of available space to install enough stormwater BMPs to meet TMDL requirements is another challenge, especially for highly impervious municipalities where most of the land is privately held.
>
> Biochar amendments offer urban communities a versatile tool to meet today's challenges and beyond 2025:
>
> - To enhance the function of existing BMPs or to revive the function of poorly or non-functioning existing BMPs,
> - To enhance the function of new structural and non-structural BMPs installed for new or redevelopment activities, and
> - As a stand-alone landscape-scale BMP (e.g., urban soil amendments).

This review covers available literature from the last 10 years of research on the inclusion of biochar as an amendment to bioretentions for the augmented capture of sediment, nutrients, and other pollution from urban stormwater runoff. This review identified 48 experiments, studies, and resources in total. The literature described bioretention and biofilter structures similarly – often as a mixture of sand and organic material with or without plants to filter stormwater for contaminants.

Therefore, throughout this review, both biofilter and bioretention structures are referred to as a bioretention, or a bioretention system. The available literature identified for this review were primarily laboratory studies and experiments exploring the removal of various pollutants from stormwater using biochar, sand, and compost or soil. Some of the studies specifically discuss the amendment of bioretention soil media (BSM) mixes, but most do not. The pollutant reductions and removal efficiencies included in Tables 5.a and 5.b are from studies that used biochar sourced from wood-based materials. The studies have variations in experimental design and the biochars used are produced under different conditions with varied particle sizes. Therefore, this review provides a range of removal efficiencies for biochar-amended bioretentions and biofilters which are impacted by factors such as:

- Biochar feedstock selection, particle size, and production conditions;
- Bioretention soil media composition;
- Biochar amendment rate;
- Stormwater properties; and
- Environmental factors.

Resources included in this review highlighted the need for additional field studies on biochar-augmented bioretention systems that include adequate data collected on the impacts of biochar on stormwater contaminant reduction and hydrologic impacts, especially within the Chesapeake Bay watershed (CBw) for nutrients and runoff reductions. Following the introduction, this review discusses the results from studies on biochar in bioretention systems in and around the CBw. Then, the section on Biochar Properties and Considerations for Urban Stormwater Management summarizes the highlighted findings.

Biochar in and around the Chesapeake Bay Watershed

Field Study

Tian et al. (2019) conducted a controlled field study of a bi-layer pilot-scale bioretention cell in Newark, DE. While the study was not conducted within the Chesapeake Bay watershed boundary, it was deemed close enough in proximity (< 10 miles) to include in this section of the literature review. The study investigated hydrologic performance and nitrate removal efficiency of biochar and zero-valent iron (ZVI) amendments. The control design for the experiment from bottom-to-top included: a 5 cm layer of rice gravel for the drainage layer, a 15-cm saturation zone filled with coarse (0.15 – 1.0 mm) sand, 76-cm Vadose zone of standard bioretention media (62% C33 sand, 11% fines, and 27% sawdust by volume), and, finally, a 5 cm layer of shredded hardwood bark mulch was applied for protection. The modified bioretention system designed for the study amended the Vadose zone bioretention media with a wood-based biochar (Soil Reef™ biochar from the Biochar Company – Berwyn, PA) at a rate of 18% by volume). The saturation zone's coarse sand was amended with ZVI at a rate of 10% by volume. Plants were not included in either the control or modified bioretention systems.

The study was able to separately assess the water retention in the biochar layer and ZVI layer and quantify the event specific and cumulative efficiencies for removing NO_3-N. Four stormwater infiltration tests were conducted over an 18-month period with synthetic stormwater solution. For the synthetic stormwater solution, dechlorinated tap water spiked with Br^- (as KBr) at ~90 mg/L and NO_3-N (as $NaNO_3$)at ~10 mg/L. When compared to the control bioretention cell without biochar or ZVI amendments, the amended bioretention cell showed greater water retention, longer residence time, and higher nitrate removal. The biochar-amended layer removed 30.6 – 95.7% of nitrate whereas the control removed -6.1 – 89.6% (Tian et al., 2019). Biochar increased water retention[1] by 11 - 27% while preventing clogging and loss of infiltration capacity (Tian et al., 2019).

In 2024 Chowdhury et al., published a study that evaluated the use of biochar to improve water retention and transmission at multiple sites with varying biochar applications (0%, 9%, and 17% bv) were amended to soils between impervious pavement and pervious grassed slopes. saturated hydraulic conductivity (Ksat) and easily drainable water storage capacity were monitored at 2 sites for both 5 months and 15 months. The results from this study presented a significant increase in Ksat, drainable water storage capacity, and plant available water content (AWC) at application rates of 17% when compared to undisturbed soils. Averaged across the four (4) field test sites, Ksat increased by a factor of 7.1±3.1 SE, field capacity (FC) increased by a factor of 2.0±0.3 SE, and AWC increased by a factor of 2.1±0.3 at a 5-10 cm soil depth. Additionally, the study results suggest that biochar amendment "increased the organic matter content, aggregate mean weight diameter, organo-mineral content, and fungal hyphal length while reducing bulk density" (Chowdhury et al., 2024).

Chowdhury et al.'s (2024) study proposed that the formation of water stable aggregates are "a key mechanism by which biochar enhances water infiltration." Soil aggregates are groups of soil particles that bind to each other more strongly than to adjacent particles – in layman's terms this could be described as the ability for soil to clump together. Water stable aggregates are an important metric for soil health as it is a measure of how stable a soil is when wet. Water stable aggregates are responsible for soil properties such as erosion resistance, gas diffusion, and water infiltration (NRCS, 2008).

The study suggests that biochar's effect on the increase in organo-mineral associated content – which increases soil binding – and fungal hyphal length – which improves the binding of micro- and macro-aggregates – enhances the formation of water stable aggregates (Chowdhury et al., 2024). Averaged across all four(4) sites, the 17% bv biochar amendment was found to significantly increase the total water stable aggregate fraction by 41±10% compared to undisturbed soil. While the mean weight diameter (MWD) of the aggregates increased by 62±25% compared to undisturbed soils (See Table 1).

[1] Water retention increase is based on the mean volumetric water content in the vadose zone of the bioretention cells. Volumetric water content was measured by 6 soil moisture sensors. These sensors were placed within the bioretention soil media starting at a depth of 5 cm. The study does not include surface ponding in the bioretention cells as a part of the volumetric water content measurements translation to an increase in water retention.

Table 1. Biochar's impact on soil properties related to water stable aggregates (Chowdhury et al., 2024). Results are the average of all four (4) field test sites.

Total Water Stable Aggregate Fraction	+41±10%
Mean Weight Diameter (MWD)	+62±25%
Organo-Mineral Content	+2.8±0.8SE
Fungal Hyphal Length	+1.4±0.1 SE

The findings based on differences between field sites "indicate that biochar's effect on wet aggregate stability is more pronounced in urban soils with lower organic matter content over time" (Chowdhury et al., 2024). This study highlights the potential of wood-based biochars to increase more and larger water stable aggregates and improved water retention and infiltration in soils and soil media. While Chowdhury et al.'s (2024) study does not directly address the use of biochar in a bioretention or biofilter, these findings are applicable to the use of biochar in these types of urban green infrastructure that depend on infiltration and water retention for effectiveness.

Lab Study

Akpinar et al. (2023b) studied the time-dependent impact of wood-derived biochar on particle aggregation, the relationships between aggregation and stormwater retention, hydraulic conductivity, and the growth of plants in two representative bioretention soil media (BSM) mixes. The experiment was conducted in a plant growth chamber at the University of Delaware in Newark, DE. The two BSMs were designed to align with the BSM requirements from North Carolina and Delaware, referred to as the NC mix and DE mix, respectively. The NC mix was composed of 88% C33 concrete sand, 8% fines, and 4% sawdust by volume. The DE mix was composed of 60% C33 sand, 30% mulch, and 10% compost by volume. The biochar used was sourced from The Biochar Company in Berwyn, PA – Soil Reef™. The same biochar was used for Tian et al.'s (2019) experiment.

The representative BSM mixes were packed into cylindrical pots. Each pot was planted with one plug of switchgrass and subjected to weekly "storms" for 20 weeks followed by a 10-week dry period. The synthetic storm solution "contained dissolved solids (120 mg/L of $CaCl_2$), phosphorous (3 mg/L of Na_2HPO_4 as P), nitrate (2 mg/L $NaNO_3$ as N), ammonium (2 mg/L NH_4Cl as N), and the pH was adjusted to 7.0±0.1 using 1 M HCl or 1 M NaOH" (Akpinar et al., 2023b). The five control pots for each BSM mix did not include plants. The five BSMs tested were:

- Unamended NC mix
- NC mix amended with 9% biochar by volume
- NC mix amended with 18% biochar by volume
- Unamended DE mix
- DE mix amended with 18% biochar by volume.

The study documented the increase of saturated hydraulic conductivity (Ksat) in the NC mix over time and based on the biochar rates and plant growth (See Table 2). While the DE mix showed a negligible effect at a 18% biochar rate as the saturated hydraulic conductivity decreased with an increase in biochar rate.

Table 2. Saturated hydraulic conductivity measurements from Akpinar et al. (2023) for unplanted (0 weeks) and planted pots (30 weeks) in the NC media mix. There was no statistically significant change at 0 weeks based on biochar rates.

BSM Media	Biochar Rate	@ 0 weeks (unplanted)	@ 30 weeks (planted)
NC mix	0% by volume	14.9 ± 0.5 cm/h	~ 30 ± 5 cm/h
	9% by volume	15.5 ± 0.8 cm/h	~ 38 ± 10 cm/h
	18% by volume	16.3 ± 0.3 cm/h	~ 47 ± 3 cm/h
DE mix	0% by volume	24.5 ± 0.5 cm/h	–
	18% by volume	23.6 ± 1.1 cm/h	–

The DE mix showed minimal effects to the hydraulic conductivity when amended with biochar. The DE mix also showed decreased water stable aggregation, possibly due to the lack of clay and the reduction of compost with the addition of biochar. However, the NC mix amended with biochar increased the formation of water stable macroaggregates and mean weight diameter. It also showed greater fine root volume and fungal hyphae length. When compared to Tian et al. (2019), where the same BSM and biochar mixture was used (NC mix), the NC mix's dry bulk density ~20% lower in Akpinar et al.'s study. The author's noted that the hydraulic conductivity was likely increased by the packing procedure for the smaller pots used in Akpinar et al.'s study when compared to Tian et al. (2019).

Akpinar et al (2023) also discussed the impact of biochar, aggregation, and roots on water retention. The authors noted that the field capacity (FC), representing the water retained several hours after a storm event, showed a significant increase at 0 weeks for the 18% biochar rate (Table 3), while the permanent wilting point (PWP) which represents the water retained after an extensive dry period was affected minimally by the addition of biochar. However, the soil-water content that plants may easily access, or the plant available water (PAW), significantly increased at 0 weeks with an 18% biochar rate as compared to unamended BSM for the NC mix (Table 4). At 0 weeks the DE mix with an 18% biochar application rate also showed an increase in FC and PAW, though the increase was only significant for PAW.

Field Capacity

Table 3. Field capacity (FC) results from Akpinar et al. (2023) comparing NC and DE mixes at 0 and 30 weeks at biochar rates between 0%, 9%, and 18% by volume.

BSM Media	Biochar Rate (bv, by volume)	@ 0 weeks (unplanted)	@ 30 weeks (planted)
NC mix	0% bv	16 ± 3%	19 ± 5%
	9% bv	18 ± 4%	21 ± 5%
	18% bv	23 ± 3%[2]	27 ± 4%[2]
DE mix	0% bv	~22%[3]	29 ± 3%
	18% bv	~24%[3]	33 ± 5%

Plant Available Water

Table 4. Plant Available Water (PAW) results from Akpinar et al. (2023) comparing NC and DE mixes at 0 and 30 weeks at biochar rates at 0%, 9%, and 18% by volume.

BSM Media	Biochar Rate (bv, by volume)	@ 0 weeks (unplanted)	@ 30 weeks (planted)
NC mix	0% bv	8.2 ± 1.5%	9 ± 3%
	9% bv	~9%[3]	10 ± 4%
	18% bv	12.5 ± 1.9%[2]	16 ± 2%[2]
DE mix	0% bv	~15%[3]	17.1 ± 0.9%
	18% bv	~17%[3]	19.7 ± 1.1%[2]

According to Akpinar et al. (2023), The differences in Ksat and water retention between the biochar-amended NC and DE bioretention media mixes, are likely due to likely due to the higher organic content specified for the DE mix, which intrinsically provides these benefits without biochar. Akpinar et al. (2023) identified different processes for the increased water retention in NC and DE mixes (Table 5). In their paper's conclusion, they note that the organic matter content from compost and mulch within a representative bioretention soil media with moderate sand content (i.e., DE mix) "likely reduced the influence of biochar on aggregation and root growth," and went on to suggest that "organic amendments like compost/mulch might be replaced with biochar" in locations where nutrient pollution and leaching from compost is a concern.

[2] Statistically significant
[3] Estimated percentages based on Figure 2 in Akpinar et al. (2023). Exact values were not reported in the study.

Table 5. Summarized correlation between hydraulic parameters and root and soil structure properties based on 18% biochar rate, by volume, at 30 weeks.

BSM Media	Correlations Found Impacting Increased Water Retention
NC mix	Water retention parameters (FC, PWP, and PAW) were correlated: • Positively with Mean Weight Diameter (MWD), Total Porosity (TP), fine root volume (RV_f), and below-ground biomass (BGB).
DE mix	Water retention parameters (FC, PWP, and PAW) were correlated: • Positively with Total Porosity (TP) • Negatively with Mean Weight Diameter (MWD), fine root volume (RV_f), and below-ground biomass (BGB).

Biochar Properties and Considerations for Urban Stormwater Management

Many of the studies reviewed noted the need for more biochar-amended field-based experiments. Premarathna et al. (2023) states that "the limitations of lab-based studies and the inadequacy of field-scale investigations suggest that there is still a lack of comprehensive understanding regarding the effectiveness and long-term performance of biochar in real-world bioretention applications." Biswal et al. (2022) notes the need for additional research that considers "how plant growth and phytoremediation potential are influenced by the usage of biochar as filter media" in bioretention. To address some of these research gaps and facilitate more field-scale studies, Tirpak et al. (2021) recommends that regulatory agencies that wish to promote the use of bioretention amendments should develop specifications that allow for the flexibility to include approved amendments (i.e., biochar) based on their capacity to remove target pollutants. Therefore, these knowledge gaps are an opportunity to increase and support field-based experiments with biochar within the Chesapeake Bay watershed for increased sediment and nutrient reductions from urban stormwater runoff. Highlighted findings regarding the properties of biochar and considerations for urban stormwater management outside of the Chesapeake Bay literature review are discussed in this literature review under the following topics:

- Biochar Selection
- Biochar Rate
- Biochar Particle Size
- Saturated Hydraulic Conductivity and Soil Water Retention
- Pollutant Removal
- Biochar Degradation and Long-Term Efficacy
- Potential Contaminants and Risks
- Biochar Soil Media (BSM) Mixes

Tables 5.a and 5.b at the end of the literature review presents a high-level look at the pollutant reductions and removal efficiencies from the studies reviewed. An additional Appendix A (spreadsheet) provides a more detailed breakdown of the studies' test iterations and results including biochar's impact on porosity, saturated hydraulic conductivity, as well as nutrient and sediment reductions. Some values within the spreadsheet are estimated or calculated based on the available reported information from the studies and their associated supplementary information or data.

Biochar Selection

- Specific biochars need to be individually evaluated for pollutant removal performance (Kaya et al., 2022; Boehm et al., 2020). Reviews recommend that the biochar selection for BSM amendment should be based on the pollutant(s) targeted for reduction (Kaya et al., 2022) and based on published pollutant removal capacities (Tirpak et al., 2021).
- Kaya et al. (2022) recommends the use of wood-based biochar because biochar feedstock from coarse-grained parent material (i.e., woody material) result in a coarser biochar particle when compared to other feedstocks. These coarser particles will be harder to compact in a bioretention system minimizing the impacts on hydraulic conductivity from the augmenting material. Additionally, since the woody material is xylemic in nature, containing tissues that conduct water and minerals throughout the plant when alive, the wood-based biochar is likely to have a higher surface area, or coarser nature than alternative feedstocks such as manure, making it more effective at capturing nutrients from runoff.
- Plant-derived biochars were found to "have fewer leaching concerns [than mineral-rich feedstocks (i.e., poultry litter or manure)] and wood-based biochars show the best performance" in this regard (Kaya et al., 2022).
- From Kaya et al. (2022), Figure 1 provides an initial screening process for the selection of biochar. The figure visualizes "the effect of feedstock and pyrolysis temperature on important characteristics for adsorption of metals and hydrophobic organics." Their review found that woody biochar feedstock is favorable for hydrophobic organics removal and is more likely to have a lower pH, ash content, porosity, specific surface area (SSA), and nutrient and metal leaching potential than mineral-rich feedstock (i.e., manure). Note that elsewhere in the Kaya et al. (2022) review, the authors state that "biochar produced from manure, biosolids, or solid waste feedstocks show lower surface areas, carbon content, and high CEC and nutrients contents compared to plant or wood-based biochar even at higher pyrolysis temperatures." Note that Figure 1 is believed to contain an error for the "Porosity and SSA" row. The findings both from Kaya et al.

(2024) and other biochar research consistently show that woody feedstock for biochar production results in higher porosity and SSA when compared to mineral-rich feedstocks.

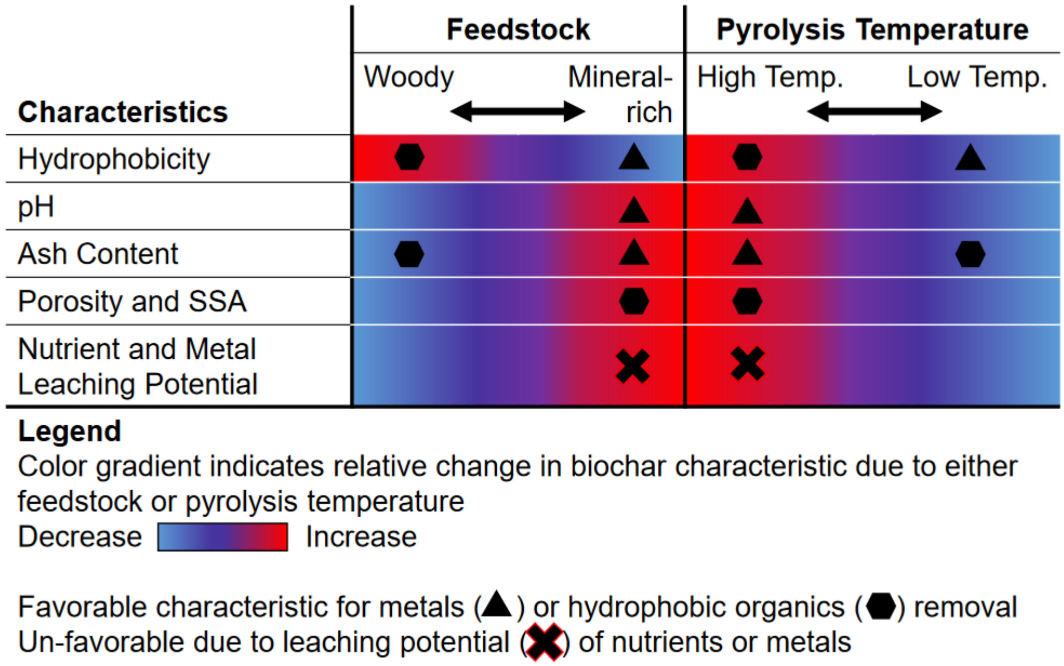

Figure 1. Effect of feedstock and pyrolysis temperature on important characteristics for adsorption of metals and hydrophobic organics (Kaya et al., 2022). Note: findings both from Kaya et al. (2024) and other biochar research consistently show that woody feedstock for biochar production results in higher porosity and SSA when compared to mineral-rich feedstocks.

Biochar Amount

- According to Biswal et al.'s (2022) review, most of the studies reported filter media containing a low amount of biochar (< 10% by mass). A few studies included a higher amount of biochar (up to 30%).

Biochar Particle Size

- Kaya et al. (2022) recommends that use of wood-derived biochars with a particle size of 0.4 – 2.00 mm for handling common hydraulic loads of stormwater. The authors also suggest "screening new media by particle size for ease of purchasing and the ability to avoid fine particles" (Kaya et al., 2022).
- Chen et al. (2022) notes that increasing biochar particle size decreases bacterial and nutrient pollutant reductions. A range of biochar particle size between 0.25 – 1.00 mm may be a good place to start, depending on the target pollutants and the necessary hydraulic conductivity. To maintain hydraulic conductivity within a bioretention, the necessary biochar particle size will sacrifice peak removal capacity of bacteria and nutrients.

Saturated Hydraulic Conductivity and Soil Water Retention

- Liu et al. (2016) found that biochar particles smaller than sand particles resulted in a greater decrease of hydraulic conductivity than biochar particles larger than sand particles, and no significant effect was noticed when biochar particle size was similar to the sand particle size. In this study, a wood-based biochar-amended uniform silica sand "increased water retention by adding water in intrapores not present in 100% sand samples" (Yi et al., 2020). The elongated shapes of the biochar particles increased the interpore volume and thus water retention.
- Lim and Spokas (2018) also found that the biochar particle sizes that were both larger and smaller than the sand grains they were combined with decreased the saturated hydraulic conductivity. However, when the biochar particle size was similar to the sand grains there was no impact on the saturated hydraulic conductivity. Smaller particles were postulated to increase the risk of clogging the pore space within the media, while larger particles were thought by the authors to increase tortuosity and the length of the water pathway when compared to the unamended sand.
- Yan et al. (2021) developed a model to predict biochar's effects on a porous medium's saturated hydraulic conductivity. The experiments conducted "showed a strong positive correlation between the interporosity of each medium and the saturated hydraulic conductivity." The model error was improved when the particle specific surface area was increased for larger biochar particles, which "indicates the importance of biochar particle shape on pore structure and saturated hydraulic conductivity." The irregular shape of biochar particles when combined with uniform sands "may reduce the size of pore openings and increase the resistance to water flow."
- The unexpected decrease in saturated hydraulic conductivity for sands amended with similar and larger size biochar particles was explained by the decrease in mean pore radii (~25%) even though biochar increased the interporosity (Yan et al., 2021). This result may inform the findings from Lui et al. (2016) and Lim and Spokas (2018) where larger biochar particles were found to reduce the saturated hydraulic conductivity.
- The purpose of Yi et al.'s (2020) study was to "develop a model to predict changes in soil water retention for soil amended with biochar by accounting for biochar's separate influence on water retained in intrapores and interpores." Water retention in biochar-amended sandy loam improved more significantly with wood-based biochar than poultry litter biochar due to the greater intrapore volume. The significant increase in water retention for increased rates of wood-based biochar in sand indicates the significant role of capillary water in biochar intrapores for increasing water retention.
- Berger et al. (2019) documented a 75% decrease in saturated hydraulic conductivity at a biochar rate of 20% within woodchip columns. The saturated hydraulic conductivity was more than "five times the observed infiltration rate." Soil water retention curves from this study show that the addition of biochar increased the water holding capacity of woodchips.

Pollutant Removal

Nutrient and Sediment

- From the Boehm et al. (2020) reviewed existing literature and found that the removal of Nitrogen-containing nutrients, Phosphorus, Total Organic Carbon (TOC), and Total Suspended Solids (TSS) in biochar augmented biofilters was similar to controls. However, Biswal et al. (2022) found that biochar-amendment in biofilter systems enhances nitrogen removal (>90%).

- From Biswal et al. (2022),Figure 2 showed nutrient removal ranges of 32-61% for total nitrogen and 45-94% for total phosphorus. These pollutant reductions were related to the characteristics of the biochar, biochar size and quantity within the system, and the biochars' C/N ratio (N by biological).

Other Pollutants

- Tirpak et al. (2021) reports that the "removal of heavy metals and nutrients with biochar is limited when compared to organics and bacteria removal." Biochar is more effective at removing certain heavy metals – lead, copper, and nickel (Boehm et al., 2020; Tirpak et al., 2021).

- Removal of microbial pollutants and trace organic contaminants (TOrCs) is generally greater in biochar-augmented materials than controls just containing sand, soil, and/or compost (Boehm et al., 2020; Tirpak et al., 2021).

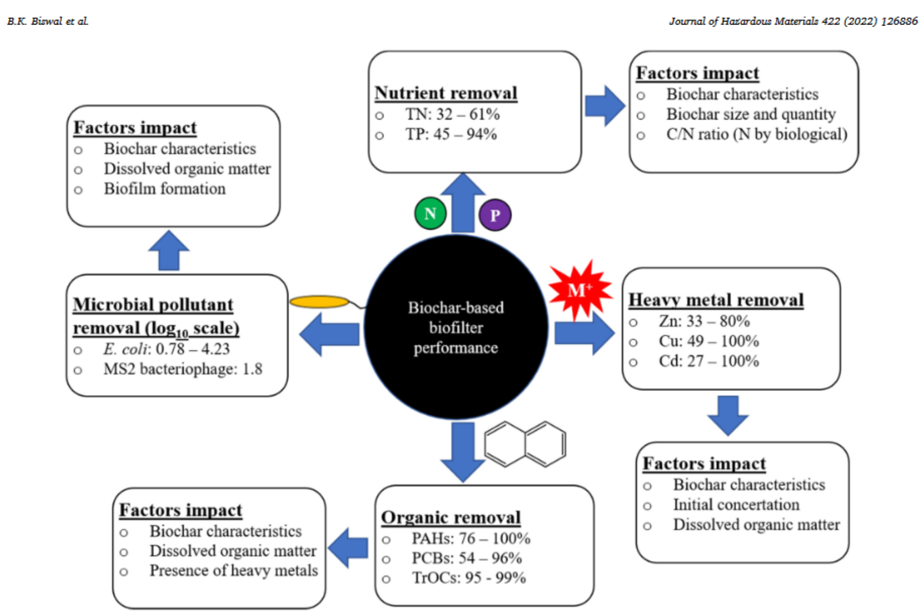

Figure 2. Biochar-based biofilter performance and important factors affecting the removal of stormwater pollutants from Biswal et al. (2022) review paper.

Biochar Degradation and Long-term Efficacy

- Boehm et al. (2020) conducted an analysis to "assess the expected potential duration of the longer-term operation lifetime for removal of chemical contaminants" with biochar-amended media. The analysis was based on 4 studies that were conducted long enough to allow the breakthrough of chemical contaminants *[organophosphate flame retardants (OPFRs), Triazines, Benzotriazoles, Diuron, bisphenol A(BPA), and metals (Zn, Az, Cr)]* (Boehm et al, 2020). The authors state that when "considering the breakthrough results and the sizing and operational assumptions from Ulrich et al. (2017) expected exhaustion times for systems with high temperature wood-based biochars could range from about five months to over seven years" for these specific TOrCs depending on the biochar production process (Boehm et al., 2020).

- Boehm et al. (2020) notes that "extreme flow conditions and freeze/thaw cycles can adversely affect *[pollutant removal]* performance and clogging or channeling can cause systems to fail long before media exhaustion is reached."
- Chen et al. (2022) reports that natural aging and freeze/thaw cycles can "generate new micropores on the surface of biochar," increasing the surface area. So "aged biochar may be more effective at reducing nutrient leaching or anionic pollutants," but the formation of biofilms may reduce the effectiveness of biochar as it ages by reducing its hydrophobicity and available adsorptions sites (Chen et al., 2022).

LEACHING AND POTENTIAL CONTAMINANTS/RISKS:

- Colloidal particles from biochar may pose a risk as contaminants can have the potential to be co-transported with fine or nano particles (Kaya et al., 2022).
- Biochar-derived dissolved organic matter can mobilize copper (Kaya et al., 2022).
- Competition for adsorption sites on biochar particles may affect the removal potential of any pollutant (Chen et al. 2022). This plays a role in heavy metal pollutant reduction efficiency (Premarathna et al., 2023).
    - Organic matter was found to interfere with adsorption by competing with contaminants and blocking available binding sites (Premarathna et al., 2023).
- N-rich biochar releases nitrogen when the nitrogen concentration inside the bioretention is low (Premarathna et al., 2023).

BIORETENTION SOIL MEDIA (BSM) MIX

- Compost may influence the efficacy of biochar when they are both included in the BSM mix. Tirpak et al. (2021) notes that some studies included in their review showed reduced bacterial removal capacity or increased biodegradation and the release of micropollutants.
- Blending amendments may be necessary to maximize the bioretention's capacity to removal a mixture of pollutants (Tirpak et al., 2021; Premarathna et al., 2023).
    - To remove multiple contaminants effectively at the same time, it may be necessary to have a combination of both slow and high temperature pyrolyzed biochar in the BSM mix (Biswal et al., 2022).

Suggested Strategies for the Selection of Bioretention Amendments

The reviews conducted by Kaya et al. (2022) and Tirpak et al. (2021) both provide an evaluation strategy for selecting biochar for augmented stormwater treatment. Tirpak et al. (2021) provides guidance for amendment selection through a decision framework based on the results of their study of different amendments for stormwater management (**Error! Reference source not found.**). The decision framework outlines the proposed process of selecting "BSM amendments based on pollutant of concern and amendment cost" (Tirpak et al., 2021). They recommend biochar for augmented management of nutrients (N and P), pathogens, and organics.

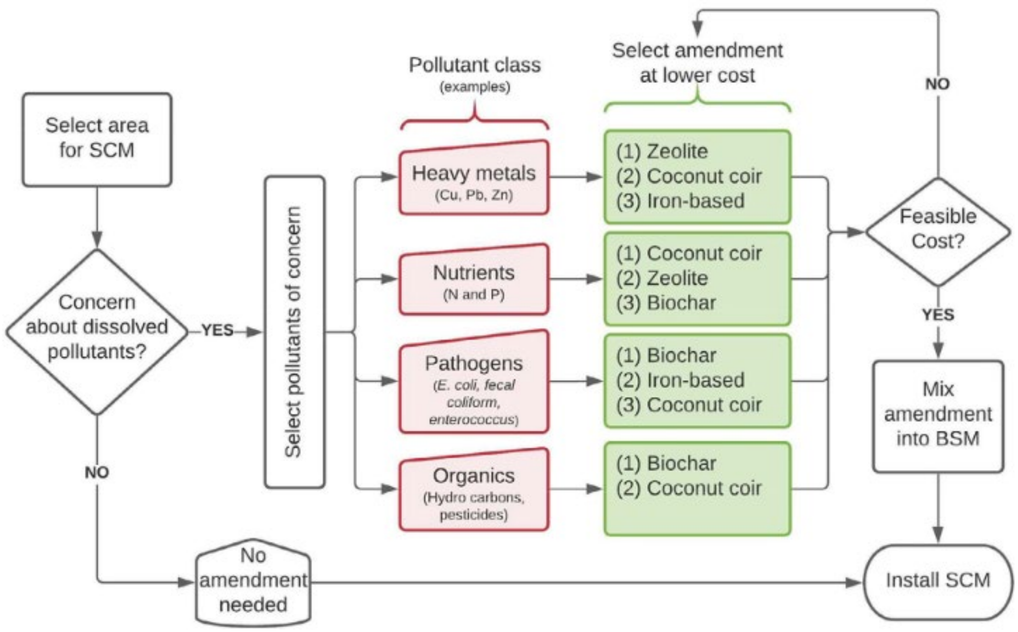

Figure 3. Tirpak et al.'s (2021) decision framework flow chart illustrating the selection of BSM amendments based on pollutant of concern and amendment cost.

The strategy from Kaya et al. (2022) is focused on the removal of contaminants of concern (e.g., PAHs, PCBs, phenols, pesticides, and heavy metals) through biochar-amended stormwater control measures. Boxes 1 - 5 in Figure 4 are described by Kaya et al. (2022) as follows:

1. Biochar characteristics and removal potential for contaminants of concern (COCs).
2. Biochar selection and particle size requirement screening.
3. Hydraulic conductivity decision.
4. Laboratory tests based on local rain fall analysis.
5. Effect of biological treatment and pilot scale studies.

While Kaya et al.'s (2022) evaluation strategy targets organic contaminants, it is a useful strategy framework for the selection and experimentation process for the selection of biochar for a specific contaminant of concern (i.e., nutrients and sediment) where different factors and specifications would be needed

Conclusion

The literature reviewed highlights several direct impacts of biochar amendment on key soil properties relevant to bioretention systems and urban stormwater management. Studies indicate that biochar generally enhances water retention, as demonstrated by increased field capacity (FC) and plant available water (PAW). For instance, Chowdhury et al. (2024) reported a two-fold increase in field capacity and a 2.1±0.3 SE increase in AWC at a 17% biochar application rate. Akpinar et al. (2023b) similarly found significant increases in FC and PAW in the NC mix with an 18% biochar rate. This enhanced water retention is partly attributed to the increased intraporosity provided by the addition of biochar. Furthermore, biochar amendment, particularly at a rate of 17% by volume, has been shown to significantly increase the formation of water stable aggregates, which are crucial for maintaining soil health and promoting water infiltration.

The impact of biochar on saturated hydraulic conductivity (Ksat) is more nuanced and depends on factors such as biochar feedstock, particle size, amendment rate, and the composition of the bioretention soil media (BSM). While Chowdhury et al. (2024) observed a significant increase in Ksat with a 17% biochar rate, other studies have reported decreases, particularly when biochar particle sizes are significantly larger or smaller than the sand particles in the media. Akpinar et al. (2023b) found increased Ksat in the NC mix with higher biochar rates over time but negligible changes or decreases in the DE mix. The decreases in the DE mix are thought to be related to the higher organic matter content from compost and mulch, which the NC mix does not contain. These findings are important because Ksat influences the rate at which stormwater can infiltrate into bioretention systems, directly affecting their hydrologic performance and ability to manage runoff volumes.

The observed improvements in water retention and Ksat (depending on specific conditions), along with the significant enhancement of water stable aggregates, underscore biochar's potential to improve the overall functionality and resilience of bioretention systems. Increased water retention can lead to greater pollutant removal by extending the contact time between stormwater and the filter media, while improved soil structure from water stable aggregates ensure sustained infiltration capacity and reduces the risk of clogging. However, careful consideration of biochar selection, particle size, and amendment rate is crucial to optimize these benefits and avoid potential negative impacts on hydraulic conductivity. The differences in results between studies, such as those observed by Akpinar et al. (2023b) in the NC and DE BSMs, highlight the importance of considering the existing organic matter content and composition of the BSM when evaluating the effects of a biochar amendment.

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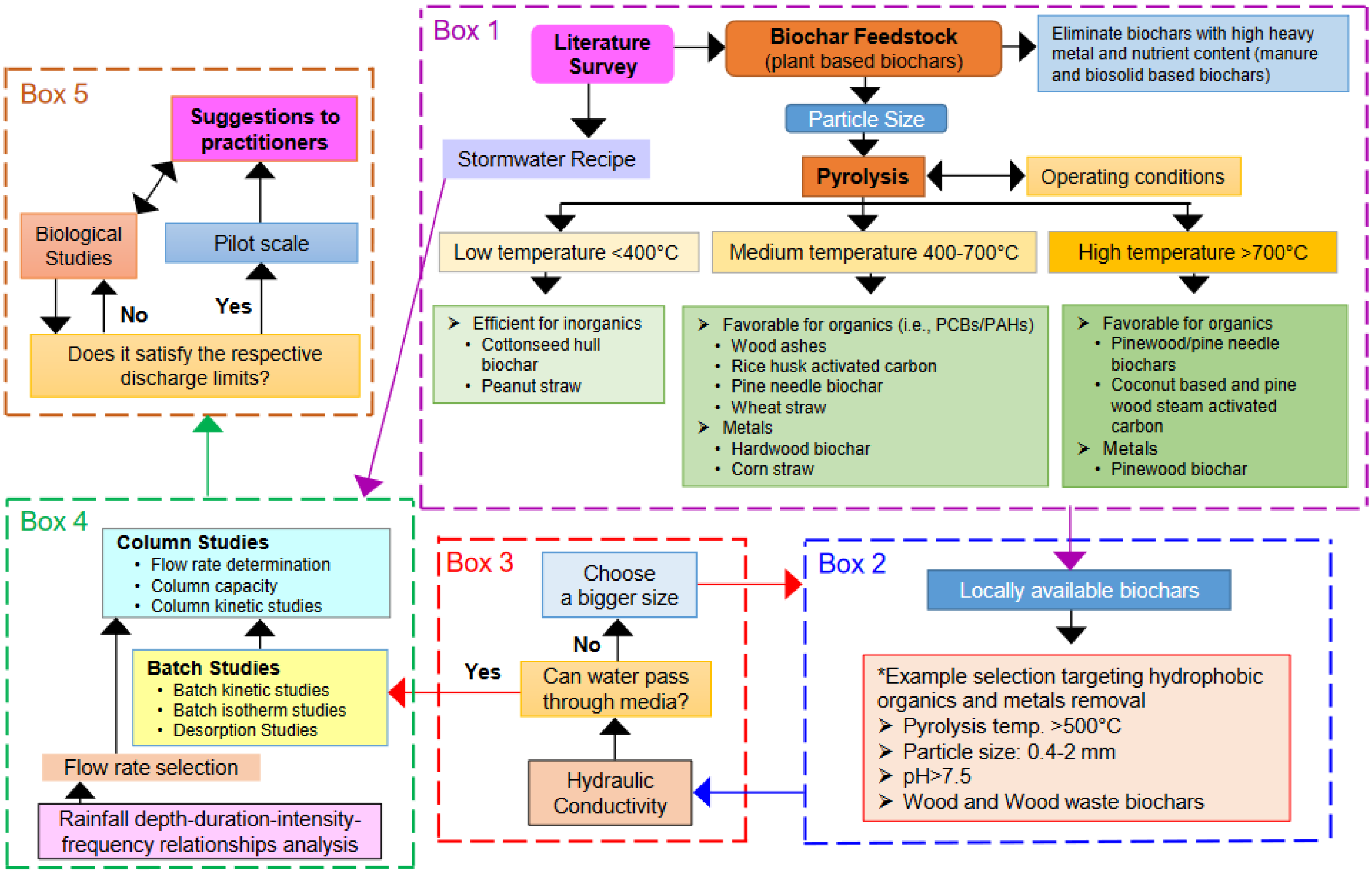

Figure 4. Evaluation strategy for biochar selection for stormwater treatment from Kaya et al. (2022). Box 1: Biochar characteristics and removal potential for contaminants of concern (COCs). Box 2: Biochar selection and particle size requirement screening. Box 3: Hydraulic conductivity decision. Box 4: Laboratory tests based on local rain fall analysis. Box 5: Effect of biological treatment and pilot scale studies.

Table 6. Removal efficiencies of pollutants and other metrics from the literature reviewed. Water Retention refers to the field capacity, water holding capacity, or volumetric water content of the biochar-amended media as reported in the studies review (See Appendix A for additional data).

Study Type	Location	Biochar Feedstock	Biochar Rate	Water Retention	Saturated Hydraulic Conductivity	Reduction/ Removal Efficiency[§]	Contaminant Reduction			Reference
							TSS	N	P	
Field	Delaware	Wood	18%	+11-27%	-	Removal Efficiency	-	30.6 - 95.7% (NO_3-N)	-	Tian et al. (2019)
Lab (Column)	Nevada	Wood (Pinyon-Juniper)	15 - 30%	-	-	Removal Efficiency	-	1.5% (NO_3-N) 14 - 21% (NH_4-N)	6.7-9.7% (OP-P)	McCrum (2017)
Lab (Column)	Delaware	Hardwood	10% bw	-	-	Removal Efficiency	-	96.4% (NH_4)	-	Tian et al. (2016)
Lab (Column)	California	Softwood	5 – 20% bv	-	5364 – 1476 mm/h	Removal Efficiency	-	30 – 100% (NO_3)	-	Berger et al. (2019)
Lab (Column)	Texas	Wood (Mesquite)	2 – 10% bw	-	-72±3%	-	-	-	-	Liu et al. (2015)
Lab (Column)	Colorado	Wood (Pine)	33% bv	-	17–34 cm/h	Reduction	-	+86% (TN) +68% (NO_3-N)	+75% (P)	Ulrich et al. (2017b)
Field	Finland	Wood (Birch)	3% bv	21-26%	-	Removal Efficiency	-	-64% (TN)**	99% (TP)	Kuoppamaki et al. (2019)
Lab (Column)	Florida	Wood	30% bv	0.053-0.059 g H20/g media	-	Removal Efficiency	-	99.52% (TAN) 50.19% (DON) 47.55% (TN)	-	Rahman et al (2020a)
Lab (column)	Illinois	Wood Pellets	100%	-	0.53 – 0.7 cm/s	Removal Efficiency	86%	86% (NO_3-N)	47% (PO_4^{3}-P)	Reddy et al. (2014)
Lab (Column)	California	Wood	30% bv	-	0.21 – 0.31 cm/s	Removal Efficiency	97-99%	-	-	Pritchard et al. (2022)
Lab	Delaware	Wood (Pine)	9 – 18% bv	18 - 27% (NC mix) 24 – 33% (DE mix)	15.5 – 47.3 cm/h (NC mix) 23.6 – 49.6 cm/h (DE mix)	Removal Efficiency	-	28 – 65% (TN) 28 – 36% (NO_3)	-19 - 0% (TP)	Akpinar et al. (2023b,c)
Field	Maryland	Wood (Fir and Pine)	9 – 17% bv	+80 – 83%	1 – 48 cm/h	-	-	-	-	Choudhury et al. (2024)

§ For the purposes of this review, "reduction" is used to describe results reported as an increase or decrease when compared to a control, and "removal efficiency" is used to describe the percentage reduction based on influent-effluent sampling.

** The negative value denotes leaching from compost. According to the research, the addition of biochar reduced TN leaching by 44%.

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Appendix A. Biochar Impacts in Bioretention

See the document attached as a separate file (Appendix A_Biochar Impact Bioretention.xlsx).