RESEARCH & DEVELOPMENT

Evaluating Biochar as a Multi-Beneficial and Cost-Effective Soil Amendment Option for Maximal Stormwater Infiltration

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16. Abstract

Compacted soils exhibit limited root growth in vegetation, reduced infiltration, and water storage, resulting in increased stormwater runoff. Biochar amended soils are a potential remedy to this issue. The addition of carbon enriched amendments such as biochar can enhance soil hydraulic properties including wet aggregate stability, water capture and hydraulic conductivity. Furthermore, biochar can be incorporated into roadside stormwater control measures (SCMs) to improve water quality, decrease pollutant infiltration, and decrease runoff. However, there is substantial variability in biochar performance based on feedstock, pyrolysis temperature, soil properties, and biofilter design. In this project, eleven different biochar supplies were used as amendments within two different North Carolina clay soils. Variations in physicochemical properties, including sieve analysis, hydrometer analysis, pycnometer density, dry bulk density, methylene blue adsorption capacity, and heavy metals analysis were analyzed. Additionally, hydraulic properties were evaluated through tests for water retention and saturated and unsaturated hydraulic conductivity. Soil-amended biochar samples were then evaluated for their contaminant removal properties for nutrients, indicator bacteria, and heavy metals through batch tests. Results of the physicochemical and batch testing were used to select the biochar samples that would be utilized in a year-long column study. Overall, several studies displayed increased contaminant removals which compared to the control (soil-only column), and their effectiveness generally decreased overtime. Outcomes of the laboratory study were aggregated into a biochar vendor webtool that juxtaposes ordering information with generalized laboratory results for each biochar to aid future selection of biochar products for field studies and applications. Contaminant removal efficiencies were also integrated into a triple bottom line (TBL) workbook developed to visualize scenario-based costs and benefits (economic, environmental, and social) for green infrastructure with and without biochar amended soils. The performance data, webtool, and TBL workbook can be used to procure biochar supplies, select biochar type based on desired outcomes, and evaluate tradeoffs between potential costs and benefits of future biochar-amended green infrastructure projects.

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EXECUTIVE SUMMARY

Departments of Transportation (DOTs) are challenged to meet regulations for stormwater runoff in soils compacted during the construction process. Compacted soils exhibit limited root growth in vegetation, reduced infiltration, and water storage, resulting in increased stormwater runoff. Biochar amended soils are a potential remedy to this issue. The addition of carbon enriched amendments such as biochar can enhance soil hydraulic properties including wet aggregate stability, water capture and hydraulic conductivity. Furthermore, biochar can be incorporated into roadside stormwater control measures (SCMs) to improve water quality, decrease pollutant infiltration, and decrease runoff. Often categorized as low impact development (LID) and green infrastructure (GI), SCMs such as sand filters, filter strips, bioswales, infiltration trenches, and bioretention systems can incorporate biochar to achieve and improve outcomes. However, there is substantial variability in biochar performance based on feedstock, pyrolysis temperature, soil properties, and biofilter design. For example, hydraulic conductivity generally decreases with biochar applications in sand media, but increases in other circumstances, including with compost mixtures, clay soils, and in tilled roadside silt loam soils.

In response to the variability of biochar performance as reported in prior literature, we completed a comprehensive literature review that was focused on identifying biochar traits associated with increased infiltration, nutrient removal, bacterial removal, and heavy metal removal. We found that despite the presence of extensive and robust scientific studies, there is vast variability in soil type, biochar type, and desired performance outcomes and applications of biochar use as a soil amendment. These limitations have proven difficult to glean specific, clear, and field-tested patterns. Additionally, there is promising evidence that biochar amendment, either incorporated in direct application to roadside soils or in engineered biofiltration media, can benefit SCMs. Biochar's high porosity, ability to improve soil structure, and influence on hydraulic conductivity, retention, and adsorption are all promising performance outcomes based on this literature review. Additional key findings include: (a) wet compaction is best across soil and biochar types; (b) porosity increase, bulk density decrease, and Ksat increase in clay soils; (c) biochar can assist with microbial communities and denitrification; and (d) increased resilience to compaction and erosion with biochar amendment in soil structure. In addition, we observed that the lack of field scale research was the largest gap in biochar amendment studies for stormwater contexts. Several researchers cited in this review suggest longer-term and field studies to conduct robust field scale projects for roadside amendments.

Eleven biochar products from eight suppliers across the U.S. were identified and characterized for potential future use as soil amendments to North Carolina clay soils. During the vendor study, special focus was given to obtaining and cataloging price, physical and chemical characteristics regarding the feedstock type, reported pyrolysis conditions, carbon storage, and particle size distribution for each biochar type. Each vendor was asked to supply a product data or spec sheet along with lab analysis for a recent shipment, and information regarding their certifications. Our vendor study was centered on suppliers capable of providing large quantities of biochar to fulfill the scale of NCDOT's operations. All of the suppliers utilized a variation of wood feedstock at pyrolysis temps ranging from 300 to 900 degrees Celsius. Results of the vendor study are combined with an overview of results from the laboratory study and presented in a webtool (https://coefs.charlotte.edu/jrice35/ncdot-biochar-webtool/) to aid in the future selection of biochar materials.

Variations in physicochemical properties across the biochar samples were analyzed through laboratory-based testing performed to evaluate the basic physical properties of the soil, biochar, and their mixture. These properties include sieve analysis, hydrometer analysis, pycnometer density, dry bulk density, methylene blue adsorption capacity, and heavy metals analysis. Hydraulic properties for biochar amended soils were evaluated through tests for water retention and saturated and unsaturated hydraulic conductivity. The physicochemical properties of biochar show that each biochar has a different particle size, dry bulk density, and pycnometer density. This results in different porosity and void ratio between the biochar soil mixtures. The higher porosity of the biochar helps in improved saturated hydraulic conductivity. Also, the biochar can have higher moisture content than the soil sample only, which was found through HYPROP and WP4C testing. The higher surface area of biochar helps in the contaminant's removal and Methylene blue adsorption capacity of the biochar shows that most of the biochar has a higher surface area.

Next, we investigated how these properties carried over into contaminant removal efficiencies. Nutrients (total phosphorus, ammonia, nitrate, and nitrite), indicator bacteria (total coliform, fecal coliform, *Enterococci*, and *E. coli*), and heavy metals (Copper (Cu), Aluminum (Al), Chromium (Cr), Magnesium (Mg), Manganese (Mn), Lead (Pb), and Zinc (Zn)) were analyzed for each sample. Batch testing was conducted to determine the removal efficiency of contaminants at two different biochar content levels: 3% and 6% by weight of the soil. The selection of biochar was based on the performance from batch testing and saturated conductivity with biochar soil mixture at two different percentages of biochar at 3% and 6% by the weight of the soil. The performance of biochar for methylene blue adsorption capacity and porosity were also taken into consideration for deciding biochar type and percentage for the column study. Eight columns have been installed which consist of one control (Soil only), Wakefield (WF), Blue Sky (BS), , Naked Char (NC), Char Bliss (CB), Biochar Now Medium (BNM), and Biochar Now Small (BNS). The concentrations of biochar in all the columns were 6% by the weight of the soil except Biochar Now Small with both 3% and 6%. Throughout the course of one year, the column effluents were analyzed at nine different time intervals to assess the performance of the selected biochar materials. We evaluated removals for three scenarios, including baseline conditions, pre-and-post drying period, and aged materials. And the result from column study shows that WF, NC, CB, and BNM biochar columns were the top performers for the nutrients whereas BS and BNS biochar columns showed the lowest removal efficiency. BS, NC, and CB biochar showed higher removal capacity for indicator bacteria analysis and the lowest performing biochar were BNM and BNS. Al, Cu, Cr, and Mn heavy metals were easily captured by BS, CB, and NC whereas BNM and BNS showed the lowest added benefits. Less metals uptake with biochar could be attributed to the higher concentration of heavy metals in the biochar. Over the period of nearly a year, the columns exhibited a reduction in contaminant removals (see Table 1). All raw data for nutrient and metal analysis have been provided as MS Excel Files. Overall CB, BS, and NC biochar showed comparatively better performance and were least affected by the aging.

Table 1 Median percent removal of contaminants from the different biochar column throughout the year. Positive median removal for more than 20% is highlighted in blue whereas negative removal is highlighted in red.

Biochar type	WF	BS	NC	CB	BNM	BNS 6%	BNS 3%
Phosphate (mg/l)	54%	-65%	52%	23%	51%	39%	63%
Ammonia (mg/l)	57%	82%	47%	89%	14%	-1%	14%
Nitrate (mg/l)	37%	74%	53%	75%	45%	43%	14%
Nitrite (mg/l)	63%	80%	93%	84%	37%	11%	47%
Total coliform (/100mL)	76%	62%	70%	93%	1%	64%	81%
***E. coli* (/100mL)**	99%	99%	72%	100%	33%	99%	99%
Fecal coliform (/100mL)	78%	66%	91%	98%	-8%	88%	94%
***Enterococci* (/100mL)**	65%	7%	73%	91%	-308%	67%	83%
Al (mg/l)	6%	38%	39%	35%	-89%	8%	42%
Cu (mg/l)	4%	5%	7%	6%	-3%	71%	-9%
Cr (mg/l)	27%	10%	11%	3%	38%	34%	22%
Zn (mg/l)	68%	46%	48%	52%	33%	26%	48%
Mn (mg/l)	65%	99%	66%	99%	67%	43%	46%
Pb (mg/l)	-3%	51%	-41%	-2%	-34%	-46%	-3%
Mg (mg/l)	2%	26%	-22%	15%	24%	20%	-8%

The ability for green infrastructure to retain water in soils and filter out pollutants from runoff are well established benefits for these systems. However, the added social and ecological benefits are not traditionally weighed in the decision to implement green infrastructure and low impact development strategies for stormwater management. Recent focus on holistic watershed management (i.e., One Water Approach) departs from conventional centralized approaches. The approach is grounded in the triple bottom line, that aims to achieve a strong and prosperous economy, high quality of life, and a healthy environment. Assessing the 'benefit function' is an emerging key concept useful for evaluating green stormwater infrastructure that mathematically expresses multiple benefits generated by the practice. Recent work demonstrates the ability for modeling tools to capture and quantify co-benefits (such as improving aesthetics, increasing biodiversity, and mitigating heat island effect) associated with healthy landscapes. Here we evaluate these additional benefits by framing each added benefit through a Triple Bottom Line (TBL) lens. The concept of the triple bottom line assesses the effectiveness of GI in promoting social, environmental, and financial benefits, known as the 3Ps: people, planet, and profit.

A TBL workbook was developed to visualize scenario-based costs and benefits for green infrastructure and green infrastructure amended with biochar. Economic metrics for estimated GI construction costs, maintenance costs, and increased neighboring property values are provided on the main dashboard and juxtaposed against environmental and social components. The environmental module estimates benefit for carbon sequestration, improved water and air quality, and ecosystem benefits (pollinator support, native habitat support, and biodiversity support). Within the social module, several indicators centered around community support and community demographics are utilized. Specifically, these include social acceptance, aesthetic potential, potential for asthma incidence reduction, potential for education improvement, intersection with potentially underserved populations (per North Carolina Department of Environmental Quality [NCDEQ] definition) and the potential to improve a lack of green space. Outcomes of the dashboard are meant to illustrate comparatively across different scenarios the potential tradeoffs in specific costs and benefits based on user defined details for GI type, size, and location.

The outcomes of this project serve as steps toward the strategic implementation of biochar as a stormwater best management practice with environmental and economic benefits to stormwater management. The information and tools gained through this project will enable NCDOT to identify and procure biochar samples based on their performance outcomes for hydraulic improvements and removal capabilities. Utilizing this information and technology delivered through this project, NCDOT will be able to implement field tests with the biochar selected in this project, select biochar based on site performance requirements (stormwater capture vs. treatment) as gleaned through the biochar vendor locator webtool, apply knowledge gained from biochar performance and added benefits to update the current NCDOT Stormwater Best Management Practices.

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LIST OF ABBREVIATIONS AND ACRONYMS

ACS	American Community Survey
AG	Aries Green
Al	Aluminum
BMP	Best Management Practice
BNC	Biochar Now Chip
BNM	Biochar Now Medium
BNS	Biochar Now Small
BS	Blue Sky
CB	Char Bliss
Cr	Chromium
Cu	Copper
DI	Deionized Water
DOT	Department of Transportation
GI	Green Infrastructure
ICP-OES	Inductively coupled plasma-optical emission spectrometry
LID	Low Impact Development
Mg	Magnesium
Mn	Manganese
MPV	Median Property Value
NC	Naked Char
NCDEQ	North Carolina Department of Environmental Quality
NCDOT	North Carolina Department of Transportation
NLCD	National Landcover Dataset
Pb	Lead
PV	Property Value
SCM	Stormwater Control Measures
SR	Soil Reef
TA	The Anderson
TOrC	Trace Organic Chemicals
TBL	Triple Bottom Line
WF	Wakefield
WTP	Willingness to Pay
Zn	Zinc

1. INTRODUCTION AND RESEARCH OBJECTIVES

1.1 Introduction

Stressors applied to soils during the construction process often lead to compacted soils exhibiting limited root growth in vegetation and reduced infiltration and water storage that results in increased stormwater runoff. Biochar amended soils are a potential remedy to this issue. The addition of biochar can play a significant role in the alteration of hydrologic properties, nutrient dynamics, soil contaminants, and microbial function.[1] Strategic implementation of this new approach potentially provides an environmental and economic benefit to stormwater management by improving the ability of soils to capture and treat stormwater. Recent research has acknowledged that green stormwater infrastructure not only improves water quality and reduces stormwater runoff but also provides social and ecological benefits (e.g., creating green jobs, improving aesthetics, and increasing biodiversity). As urban stormwater regulators and managers explore decisions about the use of stormwater best management practices towards holistic watershed approaches, they need to evaluate triple bottom line considerations (i.e., financial, social, and ecological). This proposed study assesses the ability of biochar to improve water capture and contaminant removal when amended to soils present in North Carolina and create a triple bottom line framework that captures co-benefits of biochar amended soils to assist in planning and implementation efforts. Additionally, this study will highlight the added-value of NCDOT project sites that are not fully captured under North Carolina's current regulatory framework.

Research Need Definition

Disturbed soils from roadway construction often are characterized by reduced soil porosity, infiltration rates and storage capacity, yielding increased stormwater runoff. North Carolina Department of Environmental Quality (NCDEQ) has recently recognized soil improvement as a stormwater best management practice (BMP). NCDOT currently uses compost in conjunction with tillage or scarification to improve soil conditions. Recent work has demonstrated biochar's ability to improve water capture and contaminant removal for some soils; however, studies tailored towards specific North Carolina soils have not been performed. Therein lies need in evaluating biochar's performance to assess application rates that are beneficial and cost-effective. In addition to improved hydraulic properties of biochar amended soils, social and ecological benefits of healthy landscape (e.g., improving aesthetics and biodiversity) are also achieved. An understanding of additional co-benefits of soil improvements is needed to foster a move toward more integrated and holistic watershed approaches.

1.2 Research Objectives

The overall goal of this research was to evaluate the cost-effective use of biochar for maximal stormwater infiltration and runoff quality in amended soils and assess its ability to provide social and ecological co-benefits resulting from healthy landscapes. In doing so, biochar's effectiveness was assessed over a range of application rates and clay soils native to North Carolina. Ultimately, this research will provide guidance towards the optimal selection of biochar amendment rates for soil improvement BMPs and quantifies its multi-beneficial roles within urban watershed management. Specific objectives of this work were to:

- Create a NC geospatial webtool identifying NC biochar suppliers, detailing characterization, and price for each selection.
- Perform preliminary batch testing to assess biochar application rates on contaminant removal.
- Conduct bench-scale testing (column tests) of nutrient and metal losses in biochar amended soils.
- Develop triple bottom line framework and model for assessing co-benefits of stormwater BMPs based on landscape improvements.
- Development of recommendations for optimizing biochar amendment rates for soil improvement BMPs.

2. LITERATURE REVIEW-OVERVIEW

Note: A summary of key literature findings is presented in this section. Appendix A contains the full literature review supporting this work, along with a complete list of references.

2.1 Overview

Our literature analysis included multiple related review papers and individual scientific studies to assess the current state of the science in biochar-stormwater-soil amendment research. Across the papers, there was variance in soil and stormwater composition, effects studied (e.g., compaction, metal removal, vegetation growth, drought effects), and subsequent results. Few concrete trends were present across the 50 papers reviewed, reflecting the complexity of factors influencing biochar soil amendment targets, design, and performance. However, the following four trends surfaced: (1) Biochar generally decreases bulk density and increases porosity when mixed with soils or compost (Omondi et al. 2016, Kim et al. 2021), (2) saturated hydraulic conductivity tends to increase in clay soils and decrease in sandy soils (Jeffery et al. 2015, Boehm et al. 2020), (3) nitrates and trace organic chemicals (TOrCs) have been decreased in multiple soil compositions and biofilter designs (Bock et al. 2015, Berger et al. 2019, Imhoff et al. 2019a), and (4) There is a clear need for additional field scale studies.

Additionally, very few studies were long term (Jien and Wang 2013, Herath et al. 2013, Imhoff et al. 2019a, Somerville et al. 2020). However, those that were conducted over a longer period, even under simulated conditions, were promising for the longevity of biochar in relation to compaction and erosion resilience, increased porosity, and flood mitigation (Kuoppamäki et al. 2021, Ashoori et al. 2019). Therefore, there is not only a need for field-scale, site-specific studies of biochar, but longer-term studies to understand biochar amended soil's resilience and longevity.

In Appendix A, we address multiple applications and benefits of biochar, highlighting physical and chemical properties of biochar-amended soils that influence performance for stormwater-related metrics such as hydraulic conductivity, metal and contaminant removal for water quality improvements, and other physical properties such as erosion reduction and compaction resistance. We also highlight results of existing field studies and echo current state-of the science to advocate for additional field studies and improved soil-biochar classification. We also discuss trends, disparities, and missing knowledge in the observed effects of biochar and soil composition on physical and chemical properties relevant to stormwater control measures (SCMs) such as soil performance (porosity and bulk density), water quality improvement (nutrient, bacteria, and metal removal), and water capture (pH and Ksat). Ultimately, this work leverages this literature analysis to design laboratory experiments that will contribute to the existing state of the science by demonstrating biochar outcomes with soils native to North Carolina as well as provide groundwork for field-scale roadside amendment experiments.

2.2 Key Takeaways

Despite the presence of extensive and robust scientific studies, there is vast variability in soil type, biochar type, and desired performance outcomes and applications of biochar use as a soil amendment. These limitations have proven difficult to glean specific, clear, and field-tested patterns. Additionally, there is promising evidence that biochar amendment, either incorporated in direct application to roadside soils or in engineered biofiltration media, can benefit SCMs. Biochar's high porosity, ability to improve soil structure, and influence on hydraulic conductivity, retention, and adsorption are all promising performance outcomes based on this literature review. Additional key findings include: (a) wet compaction is best across soil and biochar types; (b) porosity increase, bulk density decrease, and Ksat increase in clay soils; (c) biochar can assist with microbial communities and denitrification; and (d) increased resilience to compaction and erosion with biochar amendment in soil structure.

In addition, we observed that the lack of field scale research was the largest gap in biochar amendment studies for stormwater contexts. Researchers cited in this review suggest longer-term and field studies similar to those by Herath et al. (2013), Imhoff et al. (2017), Imhoff et al. (2019a), and He et al. (2021) to conduct robust field scale projects for roadside amendments. Their work and that of many others indicate promising longevity of biochar benefits for bulk density, porosity, saturated hydraulic conductivity, and other metrics demonstrating the significant potential of biochar.

Many authors also highlighted the relevance of macropore formation as a critical mechanism for soil structure improvement that can influence other performance metrics such as erosion, compaction resistance, hydraulic conductivity, and bulk density. Therefore, we recommend further study, classification and understanding of biochar amended soils, and changes to macropore formation. In addition to macropore formation, biochar is noted for its high porosity and influence on increasing pore sizes and altering inter- and intra- pore dynamics. Exact changes to these dynamics are reliant on soil type, particle size distribution, and other factors, but play an important yet often understudied, role in changes to soil and biochar physical and chemical properties.

In the context of this study, we focused on a small amount of studies that addressed the impacts on vegetation growth, usually in urbanized and stressed soils (e.g. Yoo et al. 2020, Kim et al. 2020, Somerville et al. 2020). In a future review, we recommend additional understanding of roadside vegetation patterns and biochar amendment because strong root structures and healthy biota also have a suite of SCM benefits for infiltration, erosion control, compaction mitigation, filtration of metals and nutrients, and runoff mitigation. Therefore, it can be inferred that if biochar enhances root zones and desired vegetation that stormwater management benefits will also increase. Additionally, the studies reviewed here indicated positive influences of biochar on retention and drought resilience for biochar amended soils, generating potential positive impacts for vegetative health in addition to SCM benefits.

To improve the state of the science, biochar-soil typification would be extremely beneficial for the future, including an analysis on application rates and most common biofilter designs or direct soil amendment ratios. While amendment percent was discussed and tested at various levels in many studies, its results indicated elevated importance which calls for future analysis of application ratios and field implementation volumes and mixtures as an important extension of these studies. Furthermore, these mixture ratios would be most valuable with a greater understanding of a typification of biofilter design or stormwater BMPs for roadside soil amendments. Mohanty et al. (2018) and the Minnesota Pollution Control Agency (2021) discuss green infrastructure (GI) and low impact development (LID) options, but there is still a disconnect from the field to the lab regarding biochar studies. For example, intricate differences in biochar performance include changes in surface water quality, retention and filtration, and subsurface properties. In many of the bioretention design and stormwater capture systems that were discussed in the literature, there were varying benefits in surface water and soil versus subsurface soil and water.

2.3 Conclusions

By investigating the current state of the science in this review, we sought to glean distinct patterns or relationships between biochar characteristics (e.g., feedstock type, pyrolysis temperature, application rate, application context) and performance outcomes (soil and water physical and chemical properties for SCMs and water quality improvement). We discovered that due to the sheer variety of these characteristics and nuances in their relationships, namely also the associated complexity of soil properties, it was difficult to sort out definitive trends. However, we did observe that in stormwater related studies, soft or hard woods were the predominant feedstock types (e.g., pine or birch), which were often produced at mid-range pyrolysis temperatures (400-600C). Moreover, fine biochars were beneficial for some metal and contaminant removal as compared to medium or coarse biochars but cause increased risk of clogging and decreases to Ksat and other priority indicators for roadside stormwater management. Biochar's high porosity and other characteristics are considered valuable for hydraulic performance outcomes but are contingent upon soil-biochar-application of which there were limited field studies.

Overall, soil structure, compaction and erosion resilience, and hydraulic properties in non-sandy media were usually seen to improve with biochar amendment. Exact performance outcomes were highly variable and contingent on study design, soil composition, biochar composition, and application rate. Due to the changes seen under field circumstances (e.g., vegetation, disruption, compaction, bacterial communities, intermittent rainfall), longitudinal (>16 weeks), site-specific studies are necessary to determine biochar performance, maintenance, and longevity. Ultimately, the increasing prevalence of biochar production and application for agricultural and stormwater benefits is promising because it can be a cost-effective and locally sustainable source of carbon enriched recycled organic material to alleviate water and soil issues. Further study and implementation of biochar is recommended because typification of soil-biochar amendments can aid in understanding a multitude of water and soil-related performance measures and outcomes.

3. DEVELOPMENT OF A BIOCHAR LOCATOR WEBTOOL

3.1 Webtool Overview

Ten biochar products from eight suppliers across the U.S. were identified and characterized for potential future use as soil amendments to North Carolina clay soils. Table 3.1 summarizes the biochar products that were used in the study. A webtool was developed to support the selection and acquisition of biochar products for future use by NCDOT. The webtool is designed to integrate outcomes of our vendor study with outcomes of the biochar characterization and lab performance. During the vendor study, special focus was given to obtaining and cataloging price, physical and chemical characteristics regarding the feedstock type, reported pyrolysis conditions, carbon storage, and particle size distribution for each biochar type. And each vendor was asked to supply a product data or spec sheet along with lab analysis for a recent shipment, and information regarding their certifications. The webtool presented here integrates outcomes from the biochar analyses that are presented in Sections 4.0 and 5.0 of this report.

Table 3.1 Summary of biochar products utilized in the study

Company Name	Product Name	Feedstock	Location	Pyrolysis Temp.
American Biochar Company	Naked Char	Wood (Southern Yellow Pine)	Niles, MI	550 – 900°C
Aries Clean Technologies	Aries Green	Wood Chip	Franklin, TN	400°C
Blue Sky Biochar	Organic Granular Pine Biochar; Organic Micronized Powder Pine Biochar	Wood (Pine)	Thousand Oaks, CA	---
Biochar Now	BN Small, BN Chip, BN Medium	Wood (Pine)	Berthoud, CO Loveland, CO	300 - 700°C
Plantonix	Char Bliss Premium Wood Biochar	Softwood	Ashland, OR	---
Soil Reef LLC	Soil Reef Biochar	Wood	Berwyn, PA	500°C
The Andersons	Biochar DG	Wood	Maumee, Ohio	---
Wakefield Biochar	Wakefield Premium Biochar	Wood (Pine)	Valdosta, GA Columbia, MO	500°C

3.2 Development Approach

Biochar characterization and results from the analysis of hydraulic and water quality improvement properties were visualized into an open-source website platform (WordPress), using Origin Pro. Origin Pro is an intuitive data visualization tool suited for collating large amounts of data into dynamic images, with the ability to export images in various formats. On the landing page, summarized results of biochar-amended soil column and batch tests are displayed in a two-toned heatmap (red-blue). Contaminant removal rates of biochar-amended soils are classified under metals, bacteria, and nutrients with respect to soil column and batch samples from the first round of tests. Removal performance rates are scaled from 0% to 100%, with lower performing biochar (i.e., reduced removal rates) colored red and higher performing biochar samples colored blue. The soil-only batch and column tests serve as a control for the biochar-amended soil samples. Blank white boxes signify negative values, where there were no noticeable changes in the batch tests, or there was an increase in contaminant deposition in the soil column. On the second section, the physio-chemical properties of each biochar-amended soil is displayed in another two-toned heatmap (red-blue). Physical and chemical properties are based on the saturated and unsaturated performances of the biochar-amended soil samples. The results for the MB adsorption, HYPROP + WP4C, and Ksat tests are shown on the website for the user's convenience. Following a similar approach, performances are ranked in percentiles with higher performances shown in blue and lower performing biochar-amended soils shown in red.

Landing page links have been provided on the webtool for further details about each biochar type used in the study. The user can simply hover on the name of any biochar and click to be directed to the pages. After being directed to the landing pages, biochar vendor information, addresses and feedstock are laid out clearly for the user's convenience. In addition, specification sheets for each biochar are provided for the user to download where available. Additional relevant information about the biochar manufacture process is provided as well.

3.3 Webtool Interface

WordPress is readily available through the university and can be easily updated to reflect any changes required by the user through a compatible web browser (e.g., Google Chrome, Firefox, etc.) The link to the webtool is as follows: https://coefs.charlotte.edu/jrice35/ncdot-biochar-webtool/ Using your personal log-in information, the page can be used to make informed decisions on evaluating the embedded benefits associated with different biochar types. Figure 3.1 is an illustration of the webtool's landing page.

NCDOT Biochar Webtool

Summarized results of removal rates

Contaminant removal rates of biochar-amended soils are classified under metals, bacteria, and nutrients with respect to soil column and batch samples from the first round of tests. Removal rates are scaled from 0% to 100%, with lower performing biochar colored red and higher performing biochar samples colored blue. The soil batch and column serves as a control for the biochar-amended soil samples. Blank white boxes signify negative values, where there were no noticeable changes in the batch tests, or there was an increase in contaminant deposition in the soil column.

Landing page links have been provided for further details about each biochar type used in the study. Simply hover on the name of any biochar and click to be directed to the pages.

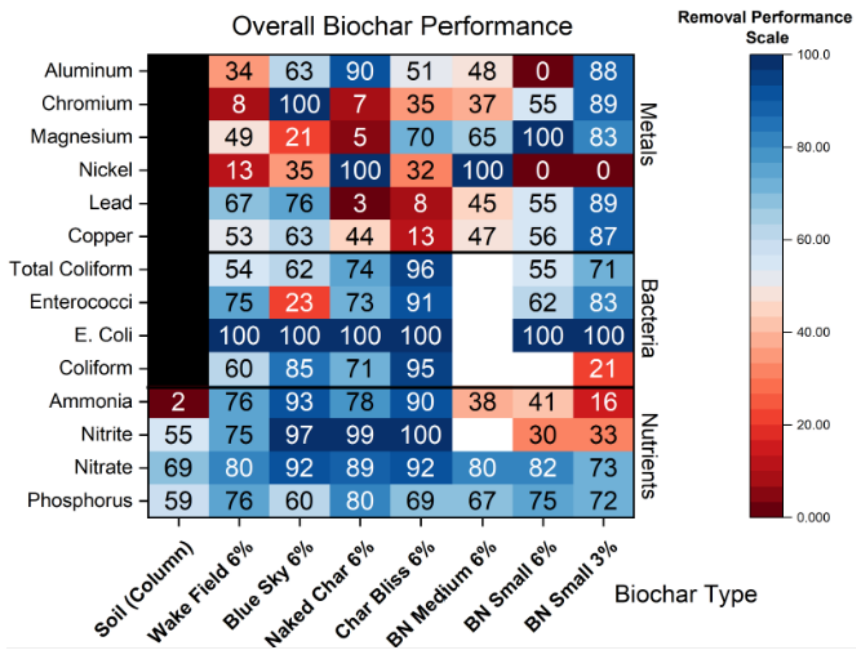

Figure 3.1 Biochar Locator Webtool (https://coefs.charlotte.edu/jrice35/ncdot-biochar-webtool/)

4. BIOCHAR AMENDMENT IMPACT TO STORMWATER RETENTION AND INFILTRATION

4.1 Physicochemical Characterization of Soil and Biochar

A thorough literature review and vendor study has been completed for this project. Based on the available information, ten different biochar have been strategically selected to conduct the physicochemical characterization with two different clay soil natives to North Carolina. Selection of biochar was made according to the source of raw material, distinctive properties, pollutant removal efficiency, and focus was given to the biochar which are available in the North Carolina region and neighboring states. Physical properties of soil, mainly hydraulic properties and removal efficiency were taken into consideration. Laboratory-based testing has been performed to evaluate the basic physical properties of the soil, biochar, and their mixture. These properties include sieve analysis, hydrometer analysis, pycnometer density, dry bulk density, methylene blue adsorption capacity, and heavy metals analysis. Standard test procedures have been followed for carrying out these tests.

4.1.1 Particle size distribution - Sieve analysis – ASTM C136/C136M – 19

Significance. This method is used to discover the representation of fine as well as coarse materials which are supposed to be used as an aggregate. In this method, a known amount of soil particles is separated into different sieve sizes to find their distribution. The obtained results are used to check the compliance of particle size distribution with certain specification requirements. Importantly, the data are also used in assessing the porosity and packing. In general, the larger the size of the particles, the higher the porosity.

Figure 4.1 Different sieve sizes for sieve analysis

Method. Soil as well as biochar samples were oven dried at 105 °C to start obtaining the constant weight (overnight drying is recommended) for ensuring the accurate measurements. As per specification, more than 300g sample for soil was taken. Whereas, the biochar is comparatively very light, more than 200g samples were used for the sieve analysis. The sample amount varies depending on the size of the sieves. However, the filled volume was kept less than the volume of a single sieve. The weight of the soil/biochar was measured on a tared pan as per the requirement. The weight of the individual sieve was measured after cleaning it with a brush for any residual particles on the sieves. The biochar/soil needs to be carefully placed on the arranged sieves in decreasing order of size from top to bottom. The sieves were placed on a mechanical sieve shaker, a mechanical sieving machine which utilizes different nature and types of agitating forces, for ten minutes and after shaking the weight of individual sieves with the biochar was measured. Each biochar/soil sample was tested in triplicate to ensure consistency.

$$\text{Average percent passing} = \frac{\text{Total weight of material} - \text{weight retained on sieve}}{\text{Total weight of material}}$$

Equation 1

$$\text{Average percent retained} = \frac{\text{Weight retained on the sieve}}{\text{Total weight of the material}} 100$$

Equation 2

Results. The results based on triplicates are summarized in Table 4.1 and Figure 4.2. The average values for percent passing and percent retained have been calculated by using the above formula. To facilitate the interpretation, the particle size of each biochar and soil sample was represented as D50 in Table 2. D50 denotes the sieve number and size above which more than 50% percent of the particles are retained. The results showed that the D50 for most of the biochar were 1.18 mm which includes Wakefield, Blue Sky, Soil Reef, Char Bliss, Biochar Now Medium, and Soil Type 1. The biochar which had a particle size greater than 2 mm includes Aries Green, The Anderson, and Soil Type 2. The 'Biochar Now' Chip had the largest D50 of 4.75 mm and as the name suggests, 'Biochar Now Small' had the smallest D50 of 0.3 mm.

Table 4.1 Percent fines by biochar type

US Standard Sieve Number	1/2"	3/8''	No.4	No.10	No.16	No.30	No.50	No.100	No.200
Sieve Size (mm)	**12.5**	**9.5**	**4.75**	**2**	**1.18**	**0.6**	**0.3**	**0.15**	**0.075**
Wakefield (WF)	100.0	100.0	100.0	98.1	80.3	43.8	23.6	10.2	4.4
Aries green (AG)	100.0	99.5	90.8	63.0	33.8	22.4	13.4	6.5	2.4
Blue sky (BS)	100.0	100.0	100.0	92.4	63.7	34.0	21.5	17.8	14.7
Soil reef (SR)	100.0	100.0	99.8	88.5	57.1	24.0	12.8	10.6	8.9
Naked char (NC)	100.0	100.0	99.3	95.0	85.8	69.4	44.1	22.6	12.1
The Anderson (TA)	100.0	100.0	100.0	73.2	13.5	1.2	0.8	0.6	0.4
Char bliss (CB)	100.0	100.0	99.9	87.8	49.8	19.1	9.4	7.9	6.8
Biochar now chip (BNC)	100.0	100.0	71.6	11.1	2.2	1.8	1.5	1.4	1.3
Biochar now medium (BNM)	100.0	100.0	100.0	89.8	54.3	20.6	3.4	2.3	1.9
Biochar now small (BNS)	100.0	100.0	100.0	99.8	99.3	90.9	52.7	5.8	2.8
Soil 1	100.0	96.1	86.7	72.4	58.4	32.8	15.0	4.5	0.8
Soil 2	100.0	99.5	90.9	62.0	48.7	37.4	29.0	21.8	14.7

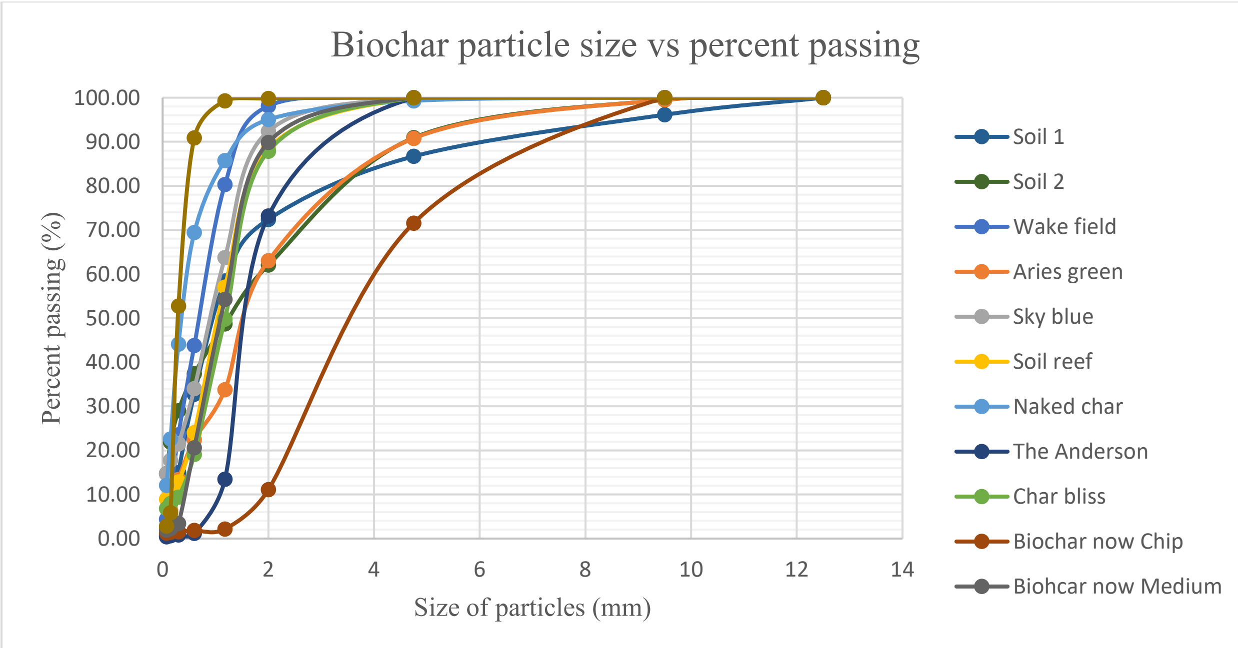

Figure 4.2 Particle size distributions for biochar and soil samples

4.1.2 Hydrometer analysis - ASTM D7928 – 21

Significance. The distribution of particle size greater than 75um (retained on sieve no 75) was determined by sieve analysis. While the particles which are smaller than 75um were analyzed through hydrometer analysis. This method gives the quantitative determination of the distribution of particles.

Method. This method precludes materials that does not have significant fines and minimum amount of fines should be at least 15 g. Because the biochar is very light and does not have significant fines, it did not qualify for this testing. Both the soil samples were oven-dried prior to the testing. After the sieve analysis, the samples which passed through the 0.075 mm sieve size were used. Per specification, 50±10 g of samples was taken a beaker, the samples were mixed with 125g sodium hexametaphosphate solution and were shaken to make a homogenous slurry. The slurry was further transferred to hydrometer steel glass. The beaker was thoroughly cleaned with the deionized water (DI) until all the particles were transferred to the steel glass. Then more DI was added to the steel glass to fill roughly 40% of the glass. Further a hydrometer instrument was used for one-minute mixing. The mixed samples were carefully transferred to one-liter graduated cylinders and filled with the DI water up to the one-liter mark. A rubber stopper was used on the top of the cylinder before the sample was inverted by hand for one minute. The cylinder was carefully placed on the table and readings were recorded every 2, 5, 10 ,15, 30, 60, 250 and 1440 minutes on an undisturbed sample.

Results. The particle size from the hydrometer analysis tests were calculated for soil samples. After making temperature correction for hydrometer readings, the percent of particle in suspension and particle diameter were calculated and are summarized in Table 4.2. The obtained result follows the curve of the particle size distribution of sieve analysis. Percent passing was plotted together with the percent passing data from the sieve analysis which is demonstrated in Figure 4.3.

Table 4.2 Hydrometer analysis table of soil

Time (min)	Hydrometer Reading (mm)	Temp (°C)	Corrected Hydrometer Reading (mm)	% Soil 1 in Suspension	% Soil 2 in Suspension	Temp Correction Factor (K)	Distance (L)	Particle Diameter (mm)
2	25	25.58	24	0.389	9.669	0.0134	12.2	0.033
5	21	25.58	20	0.324	7.567	0.0134	12.9	0.022
10	19	25.02	18	0.292	6.096	0.01349	13.2	0.015
15	18	25.02	17	0.276	5.676	0.01349	13.5	0.013
30	16	23.91	15	0.243	4.624	0.01367	13.7	0.009
60	15	23.35	14	0.227	3.784	0.01375	13.8	0.007
240	14	22.24	13	0.211	2.522	0.01393	14	0.003
1440	12	22.24	11	0.178	1.892	0.01393	14.3	0.001

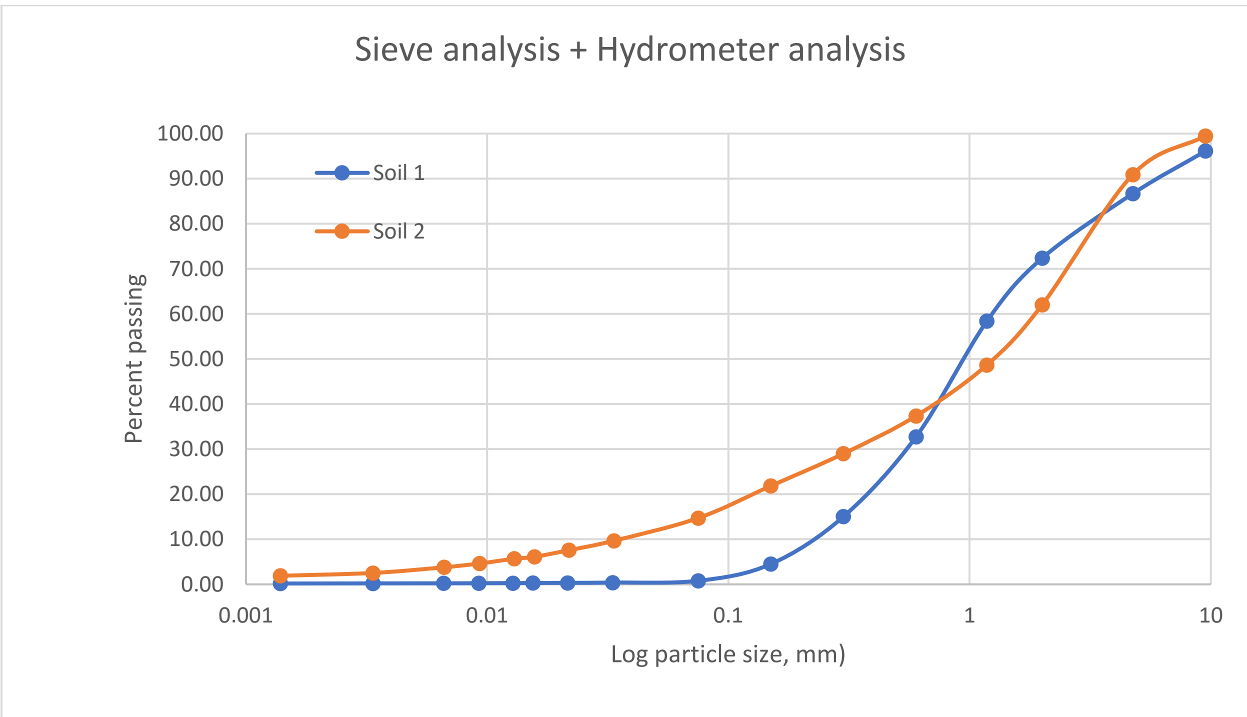

Figure 4.3 Percent passing through 0.075 has been plotted with particles analyzed with sieve. Sieve analysis was done for particles size greater than 0.075 mm

4.1.3 Pycnometer density - D854 – 06́ 1

Significance. This test is used to find the specific gravity of soil particles that are smaller than 4.75 mm by means of a pycnometer. The particles which could alter this method need not be included in the testing like fibrous matter which floats in water (highly organic solids). The specific gravity of soil solids is used for discovering the relationships such as the degree of saturation and void ratio. When specific gravity is multiplied by the density of water, it provides the density of the soil particles.

Method. Cleaned empty weight of the Pycnometer was measured. Next, the Pycnometer was filled with DI water up to the mark and the reading was taken again (Empty wt. + DI water). As per specification, 60±10 g of soil sample was measured and filled into the Pycnometer. Due to lighter weight of the biochar, the Pycnometer should not be filled to more than 40% of the volume, in the range of 15-25 g of biochar. The measured weight of the sample was then carefully transferred to the Pycnometer using a funnel. DI was used to fill up to 60% of the Pycnometer to ensure that all the particles were submerged under water. Then the Pycnometer was connected to the vacuuming unit for two hours to remove the entrapped air within the samples. Finally, it was filled with DI water up to the mark and measure the weight (Empty wt. + DI water + biochar/soil).

Figure 4.4 Pycnometer setup

$$\mathrm{Mpw,t} = \mathrm{Mp} + (\mathrm{Vp} \cdot \mathrm{\rho w,t})$$

Equation 3

Mρw,t = mass of the pycnometer and water at the test temperature (Tt), g.
Mp = the average calibrated mass of the dry pycnometer, g,
Vp = the average calibrated volume of the pycnometer, mL, and
ρw,t = the density of water at the test temperature (Tt), g/mL from

$$\mathrm{Gt} = \frac{\mathrm{\rho s}}{\mathrm{\rho w,t}} = \frac{\mathrm{Ms}}{\mathrm{M\rho w,t} - \mathrm{M\rho ws,t} - \mathrm{Ms}}$$

Equation 4

Gt = specific gravity of soil solids the test temperature (Pycnometer density)
ρs = the density of the soil solids Mg/m3 or g/cm3,
ρw,t = the density of water at the test temperature (Tt), g/mL or g/cm3.
Ms = the mass of the oven dry soil solids (g), and
Mρws,t = the mass of pycnometer, water, and soil solids at the test temperature, (Tt), g.

Results. The test was performed in triplicate to find the average pycnometer density (see Table 4.3). Studies have been conducted in the past which indicate the wet density of different biochar. For this study, ten different biochar have been used; each biochar is made up of different feedstock types. Therefore, different pycnometer density of each biochar has been expected and could be easily interpreted from the obtained result. Working with biochar for pycnometer density could be complicated as biochar are very light comparatively and might show great variation. Care needs to be given while removing the samples. The biochar should be mixed well to make it homogeneous. The result shows that each biochar has a different specific gravity varying from as low as 0.86 g/cm^3 for Biochar Now Chip to as high as 1.54 g/cm^3 for Soil Reef. The specific gravity of both the clay soils was also different. Soil 1 has lower specific gravity than Soil 2 which could be attributed to its higher organic content.

Table 4.3 Pycnometer density (Specific gravity) of biochar

Biochar Type	Pycnometer Density (g/cm^3)
WF	1.29
AG	1.12
BS	1.35
SR	1.54
NC	1.49
TA	1.33
CB	1.11
BNC	0.86
BNM	1.07
BNS	1.28
Soil 1	2.45
Soil 2	2.64

4.1.4 Dry bulk density - ASTM D7263 – 21

Significance. The dimensions and weight of the specimen are measured and then the density of the material is calculated by direct measurement. Density is a prime parameter in phase relations and mass volume relationships. The dry density of particles could be used to calculate the porosity and void ratio which is used in equation 6 when it is used with particle density (specific gravity) (Khaledi, S. et al., 2023). Densities and unit weight of recompacted samples are usually used to determine the degree of compactness. For this project, the degree of compactness was utilized during the column compaction while we tried to maintain the flow rate between 1-3in/hr.

Method. The dry bulk density of soil, biochar, and biochar soil mixtures were tested. These testing results helped in finding out the porosity of the mixture. The dried biochar and soil were mixed to make it to homogeneous consistency. A graduated cylinder of 250ml with 25cm height was used for the testing. The empty weight of the cylinder was measured and then the mixture was filled into the cylinder in three layers. The first layer was filled up to one third height of the cylinder and then compacted on its self-weight 15 times. Next, the second layer was filled up to two thirds of the total height and compacted again 15 times. Next, the third layer was filled up to the full height and compacted 20 times. At the end of the process, we ensured that the completed height was up to the mark. Finally, compacted weight of the sample was measured.

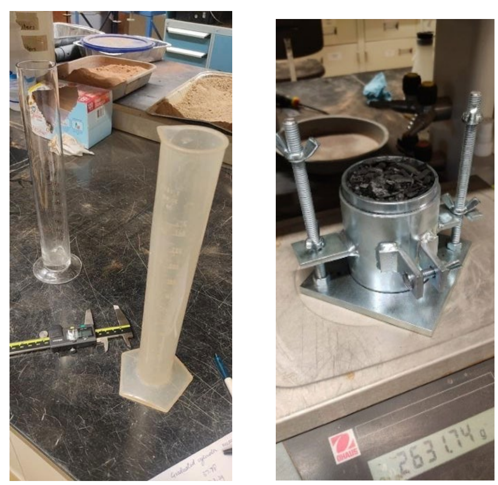

Figure 4.5 Dry bulk density setup

$$Dry\ bulk\ density = \frac{Dry\ weight\ of\ the\ biochar}{Total\ volume\ of\ the\ biochar}$$

Equation 5

Results. All the samples were performed in triplicate to find the dry bulk density of biochar with both soils. Table 4.4 shows the calculated results. This method is helpful in finding the compactness of any material. Many researchers have used its relation in their earlier studies. Various factors of biochar played an important role in generalizing the dry bulk density of the biochar (i.e., particle size, raw material, material mass). The obtained result shows that each biochar has a distinct dry bulk density. Some of them are light in weight whereas others have high particle density.

Table 4.4 Dry bulk density of the biochar with the soils at 3% and 6% by the weight of the soil.

Biochar Type	Percentage of biochar in the soil	Dry bulk density with soil 1 (g/cm^3)	Dry bulk density with soil 2 (g/cm^3)
WF	3%	1.00	1.08
	6%	0.92	1.02
AG	3%	0.88	1.02
	6%	0.79	0.93
BS	3%	0.84	0.99
	6%	0.74	0.93
SR	3%	0.73	0.98
	6%	0.65	0.89
NC	3%	0.83	1.15
	6%	0.80	1.08
TA	3%	0.90	1.23
	6%	0.87	1.20
CB	3%	0.70	0.96
	6%	0.58	0.83
BNC	3%	1.18	0.97
	6%	1.10	0.91
BNM	3%	0.83	1.33
	6%	0.75	1.27
BNS	3%	0.82	1.17
	6%	0.76	1.08

4.1.5 Porosity

Dry bulk densities and Pycnometer densities are used to calculate the porosity of the mixture, based on Equation 4.6. The results are summarized in Table 4.5. Porosity is defined as the pore space soil particles fill with either air or water. The porosity data shows that biochar can create the pores inside the biochar soil mixture. This suggests that the higher the biochar content, the higher the porosity.

$$Porosity = 1 - \frac{Dry\ bulk\ density}{Pycnometer\ density}$$

Equation 6

Table 4.5 Porosity of the biochar soil mixture at 3% and 6% biochar content.

Types of biochar	Biochar Percent by Weight (%)	Porosity with Soil 1	Porosity with Soil 2
WF	3%	0.59	0.59
	6%	0.63	0.61
AG	3%	0.64	0.62
	6%	0.68	0.65
BS	3%	0.66	0.62
	6%	0.70	0.65
SR	3%	0.70	0.63
	6%	0.74	0.66
NC	3%	0.66	0.57
	6%	0.67	0.59
TA	3%	0.63	0.54
	6%	0.64	0.54
CB	3%	0.71	0.64
	6%	0.76	0.69
BNC	3%	0.52	0.63
	6%	0.55	0.66
BNM	3%	0.66	0.50
	6%	0.69	0.52
BNS	3%	0.66	0.56
	6%	0.69	0.59

4.1.6 Methylene Blue Adsorption Capacity

Significance. The adsorption of methylene blue on the surface of the biochar provides a good indication of the presence of mesopores. The adsorption capacity of biochar differs from biochar to biochar, initial concentration, temperature, time of contact, and pH. Therefore, we measured adsorption capacity of the biochar by controlling all the pH, contact time and temperature and only varying the initial concentration of methylene blue for a particular initial concentration of biochar. Mesoporous is a material containing pores with diameters between 2 and 50 nm. For example, activated carbon.

Figure 4.6 Methylene blue adsorption test samples

Method. A standard solution of Methylene blue solution of 25, 50, 100, and 250 mg/l concentrations were prepared in the lab. And 100 mg of biochar sample was measured and placed in a 50 ml centrifuge tube. All four concentrations of 20 ml were added into the centrifuge tube with the ten different biochar type. The pH of samples was adjusted by adding either H_2SO_4 or NaOH to 6.5. Next, the samples were shaken at 180 rpm at 22C (room temperature) for 24 hours. After 24 hours, the samples are centrifuged at 4000 rpm for 10 minutes. Finally, a sample of supernatant was removed carefully with a syringe and filtered with 0.45um syringe filter paper and poured into 1 cm path length cuvette. Then the filtered solution was measured with a spectrophotometer at 665 nm wavelength.

$$\text{Percent removal} = \frac{\text{Control reading} - \text{Sample reading}}{\text{Control reading}} * 100$$

Equation 7

Results. Samples have been tested in duplicate for the methylene blue adsorption capacity. At the lower concentration of MB, higher adsorption efficiency has been found (see Table 4.6) which was further plotted in Figure 4.7. As more an adsorption surface would be available for adsorbate to be adsorbed. Lower MB showed higher adsorption due to availability of higher adsorption surface. As the concentration increases the removal efficiency decreases. Among the four different concentrations, 25 mg/l and 50 mg/l of MB concentrations showed the most removal. Wakefield, Blue Sky, Soil Reef, and Char Bliss biochar showed comparatively better adsorption removal. Nearly 100% removal efficacy could be achieved at lower concentrations with these biochars.

Table 4.6 Methylene blue adsorption capacity measurement at 665 nm for each biochar at four different initial concentrations.

Sample	Initial Methylene Blue Concentration							
	25 (mg/l)		50 (mg/l)		100 (mg/l)		250 (mg/l)	
Control	**1.724**	**Removal %**	**1.807**	**Removal %**	**1.858**	**Removal %**	**1.976**	**Removal %**
WF	0.103	94%	0.024	99%	0.486	74%	1.917	3%
AG	0.021	99%	1.796	1%	1.768	5%	1.926	3%
BS	0.021	99%	0.031	98%	0.182	90%	1.959	1%
SR	0.007	100%	0.017	99%	0.027	99%	1.874	5%
NC	0.967	44%	1.116	38%	1.610	13%	1.819	8%
TA	0.012	99%	1.237	32%	1.619	13%	1.785	10%
CB	0.244	86%	0.036	98%	0.000	100%	1.760	11%
BNC	0.054	97%	1.721	5%	1.775	4%	1.853	6%
BNM	1.705	1%	1.655	8%	1.691	9%	1.769	10%
BNS	0.577	67%	1.698	6%	1.707	8%	1.775	10%

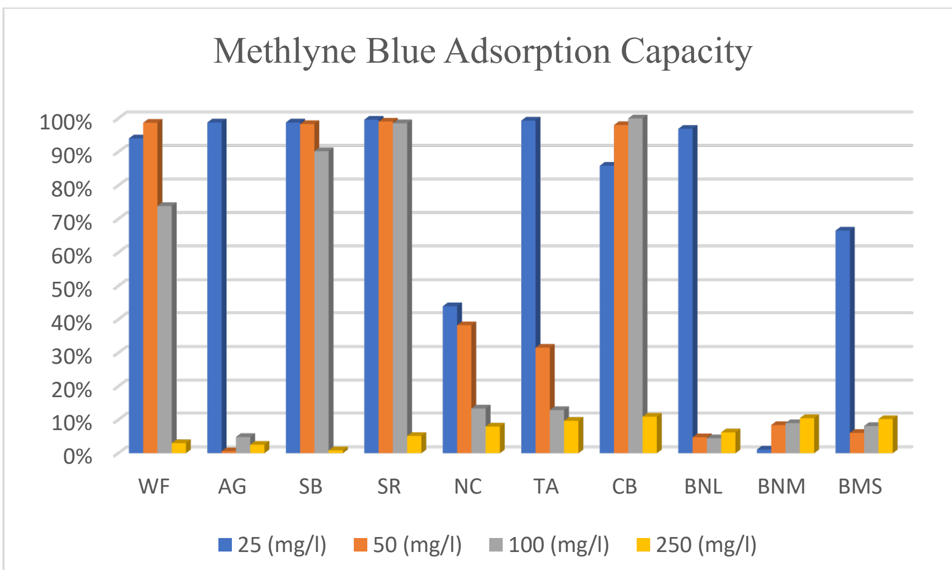

Figure 4.7 Graphical representation of biochar for Methylene blue adsorption capacity at four different initial concentrations

4.1.7 Hydrometer Analysis - ASTM D7928 – 21

Significance. Biochar and soil can add the heavy metals to the samples if they are present within the biochar. To address this concern heavy metals analysis on the oven dried biochar was done by following the study of Marmiroli et. al (2018).

Method. All the biochar and soil samples were oven dried to obtain dried samples. 1 g of samples were taken into aluminum can. The samples were burned at 550 ºC in the muffle furnace for 14 hours before the ashes were poured into a glass vial then completely submerged into the 65% nirtic acid solution. Next, the vials were heated for one hour at 165 ºC. The digested samples were diluted for 30% nitric acid by volume and then filtered out with 0.45um filter paper. Inductively coupled plasma optical emission spectrometry (ICP-OES) was used to analyze the heavy metal concentrations in the samples.

Results. The samples were tested in triplicates and the results are shown in Table 4.7. It was found that soil samples showed comparatively higher metal concentrations than the biochar samples. Al, Mn, and Mg were most abundant in almost all the samples. The higher concentrations in biochar and soil indicates the potential for heavy metals to be added to influent stormwater. Within the biochar WF, AG, BNC, and BNM showed the lowest concentrations for most of the metals. Whereas BS, NC, and TA showed the higher level of concentrations for most of the metals.

Table 4.7 Heavy metals concentrations in varying biochar and soils.

Sample	Al (mg/l)	Cu (mg/l)	Cr (mg/l)	Zn (mg/l)	Mn (mg/l)	Pb (mg/l)	Mg (mg/l)
Soil 1	2180.570	2.490	1.710	2.830	35.290	0.500	319.030
Soil 2	2182.620	2.370	2.420	3.230	40.050	0.400	588.290
WF	299.260	0.640	0.120	1.020	15.960	0.070	115.630
AG	57.120	0.980	0.790	1.600	20.660	0.040	77.550
BS	166.610	3.210	1.390	3.100	24.920	0.320	155.450
SR	185.210	4.950	4.900	1.370	30.570	0.440	199.330
NC	429.250	2.710	1.100	1.610	137.760	0.220	112.680
TA	415.980	1.290	0.280	1.150	29.490	0.490	177.360
CB	231.040	3.750	1.490	4.660	31.240	0.660	48.710
BNC	19.790	0.140	-0.020	0.760	3.760	0.010	31.160
BNM	112.100	0.850	0.050	1.450	12.410	0.050	36.210
BNS	500.970	0.980	0.430	3.700	13.310	0.160	156.840

4.1.8 Conclusion

The physicochemical properties of biochar show that it has the potential to improve the hydraulic properties of amended soils. Sieve analysis shows the representation of different particle sizes of the biochar and soil. The D50 of most of the biochar was found at 1.18 mm sieve size. Results from the pycnometer tests show a wide range for specific gravities. Where some of the biochar are light as 0.86 g/cm^3 to as high as 1.54 g/cm^3. The effect of density as well as effect of biochar application rates were also found in dry bulk density. As the biochar amount increases from 3% to 6% the dry bulk density decreases with all the biochar. The calculated porosity from dry bulk density and specific gravity validates that increasing the biochar amount increases the porosity of the mixture. And the methylene blue adsorption capacity of biochar shows a difference in adsorption capacity of various biochar which suggests the surface area of the biochar. At 25 mg/l and 50 mg/l of MB more than 90% removal efficiency has been found with biochar like Wakefield, Blue Sky, Soil Reef, and Char Bliss.

4.2 Water Retention, Saturated and Unsaturated Hydraulic Conductivity

4.2.1 Saturated Hydraulic Conductivity (Ksat)

Methods. Saturated hydraulic conductivity was measured using Ksat Meter Group's instrument following manufacturer's protocol which is ASTM D2434 compliant. The biochar and soil were mixed homogeneously to achieve consistency. For preparing the samples for Ksat testing, the sampling was attached to a circular plastic plate while keeping the sharp edge towards the top. The biochar soil mixture was filled in three layers into the sampling ring. The mixture was filled up to one third height of the sampling ring and compacted on self-weight for 15 times for the first layers. Similarly, the second layer was filled up to two thirds of the height and compacted 15 times on self-weight. Then the sampling ring was filled up to the top for the third layer and compacted 20 times to make a total 50 times compaction on its self-weight. This followed the same procedure as it was done for dry bulk density. Finally, the sample was leveled with a leveling edge and material was added or removed depending on the condition to give a smooth leveled surface. The Meter Group nonwoven cloth was used on the top with placing the saturation plate over it followed by reversing the position of the sample. The plastic plate was removed.

Then the sample was placed in a water bath with porous stone over the top covering the sampling ring. A heavy weight was placed on the top of the porous stone to protect the samples from changing shape when it starts swelling due to the addition of water. The porous stone facilitates the passing of the entrapped air through the samples. The DI water was added to the water bath at different intervals letting the samples saturate with capillary action. Finally, the sample was submerged under the water overnight for complete saturation.

Figure 4.8 Saturated hydraulic conductivity setup

Next, the overnight saturated sample was ready for the Ksat testing. The sample was transferred to the Ksat instrument from the Meter Group by attaching the gasket with a lower porous plate at the top and crown at the bottom. The sample ring has the sharp edge on the top attached to the crown specified by the Meter Group as part of the standard procedure. The DI water was de-aired overnight on a lab-based deairing instrument. The deaired water was carefully transferred to the 5-water tank standard tank provided by the Meter Group. The tank was placed overhead to allow the water to pass by the action of gravity. The de-aired DI water tube was set up to the water bottle and Ksat instrument. Next, the sample was placed on the Ksat instrument properly and fixed with a top Ksat instrument screw cap. After fixing the sample on the instrument, the valve was opened slowly to allow the de-aired water to flow through the sample. This process was continued to ensure that the sample was completely at the saturation state.

While the sample is getting saturated, the Ksat instrument was connected to the system and Ksat software was opened. As the saturated hydraulic conductivity of the samples was not very low, a falling height method was used for all the samples. With this method, the time vs the pressure head was automatically calculated by the software after starting the test. The standard protocol provided by the Meter Group was followed for the sample testing. Once the test was started, after opening the valve the reading at every small interval is automatically registered and the test automatically stops after reaching at the pressure head gap of 5 cm. That gives a plot between pressure head and time with R square value.

Results. The result illustrates that the performance of biochar mixed soil is comparatively better than the sample which had soil only with both soils. (see Table 8 and Figure 4 and 5). For soil 1, Blue Sky and Naked Char biochar did not have significant effect on the performance. The Anderson biochar reduced the filtration capacity with soil 2. The difference in performance was also observed at different application rates. As we have discussed in Task 3.1, the porosity of the samples increases by increasing the amount of biochar. As a result, the Ksat for the samples at 6% is comparatively better than samples with 3% biochar content. The difference in the performance can readily be seen from the obtained results for both soils.

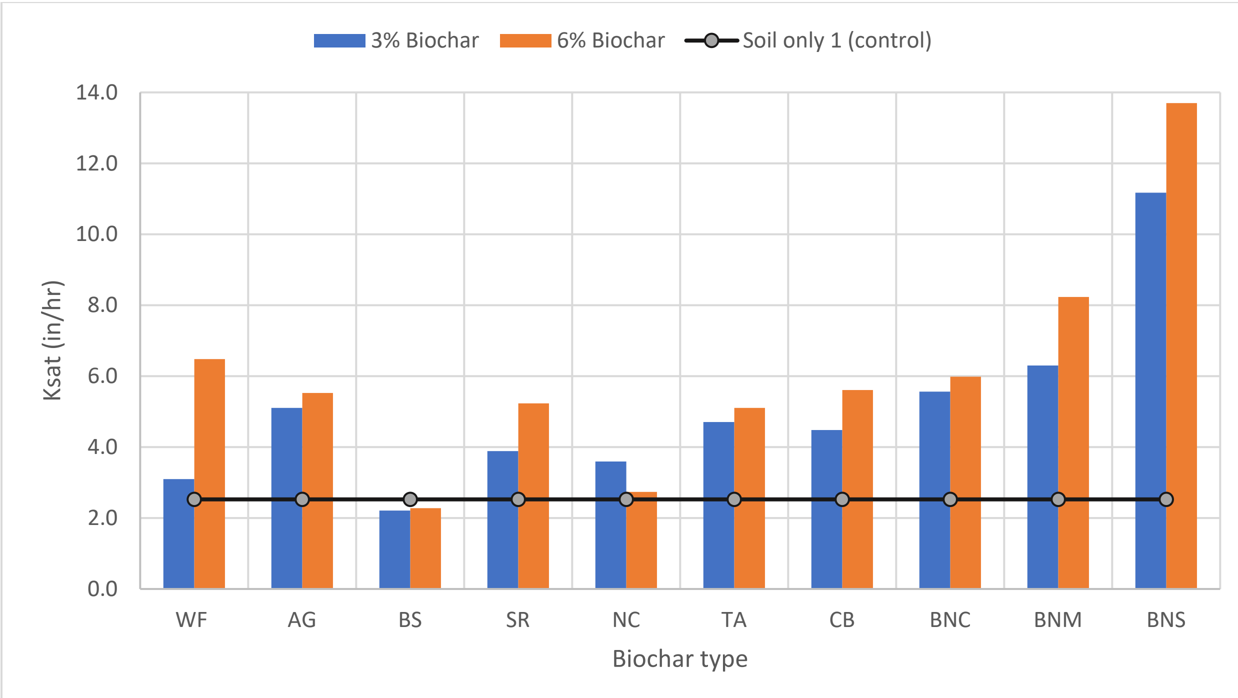

Figure 4.9 Effect of biochar on saturated hydraulic conductivity with Soil 1

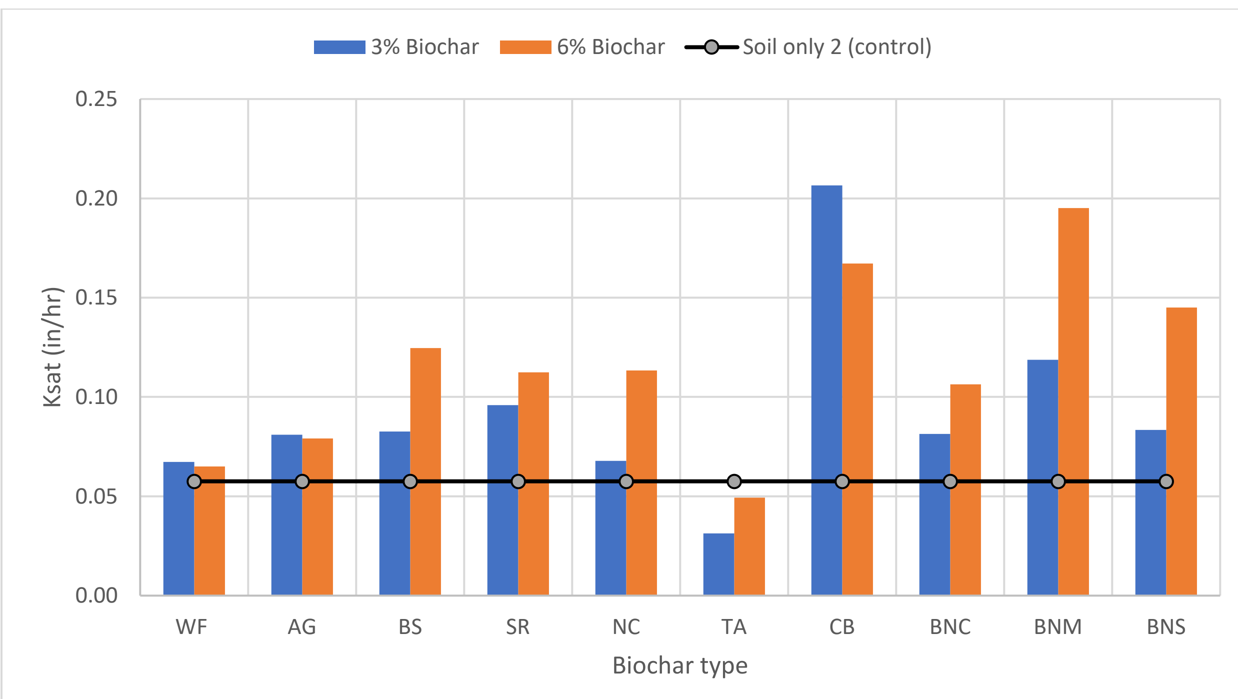

Figure 4.10 Effect of biochar on saturated hydraulic conductivity with Soil 2

4.2.2 Unsaturated hydraulic conductivity

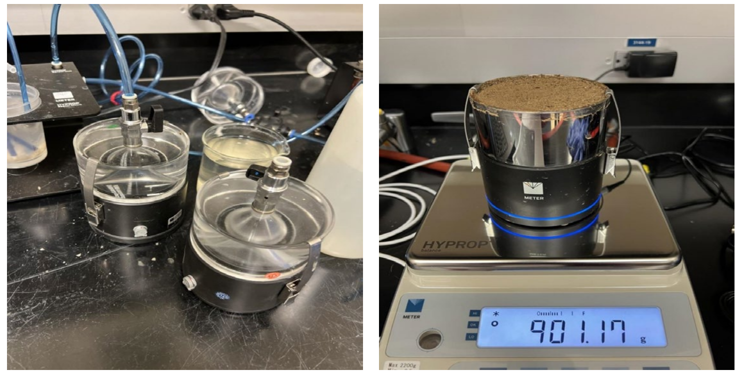

Figure 4.11 HYPROP sample test setup

Method. Hyprop Testing. Sample preparation for HYPROP and WP4C - The same sample from Ksat should be used for the HYPROP tests. For HYPROP, the saturated sample was directly transferred from the Ksat setup to HYPROP. Usually, the HYPROP set up is initiated a day in advance, where the sensor unit and both the tensiometers were de-aired overnight. The two tensiometers are placed in a small DI water bath that was connected to a motored vacuum system. The sensor unit was connected to its refilling attachment for the sensor unit and filled with DI water with a syringe. Then it was connected to another unit with the same motor vacuum system. Then it was left on the vacuum system overnight to ensure that the pressure of the set-up reaches the range of 0.9 psi.

On the day of HYPROP testing, the de-aired sensor unit setup is removed and connected to the system with HYPROP software. Once it was connected to the system, both tensiometers were placed at their respective position on the HYPROP instrument. The Meter Group specifies nine times clockwise rotation to fix the tensiometer on the instrument as well as checking with the software. Ensure that the pressure on the sensor unit from the tensiometer was not more than 200 kPa. Now the setup was ready for the sample. The sample from the Ksat tests was taken out carefully and placed on the bench after reversing its position. Then, the saturation plate was removed, and an auger guide was placed on the top. Two holes were made in the sample by using a tension shaft auger. Further, the sensor unit with the tensiometer attached was reversed and placed over the holes of the sample. Again, the sample with the sensor unit was reversed, making the sample on the top side. The whole process needs to be done carefully and quickly making sure that the sample does not lose moisture during the process. The sample with the sensor unit attached, was placed on the balance that was connected to the system. Once it is connected to the system and the sample was found on the software, sample details were provided, and a test was started. The software recorded the release of moisture at room temperature at intervals of one minute. The test continued until the tensiometer cannot record the reading. Usually, the entire testing procedure takes a week.

WP4C Testing. Once the HYPROP test is done the sample was taken for the WP4C study. The WP4C determines the relative humidity of the air above the sample in a sealed chamber conforming to ASTM D6836. The relative humidity is determined using the chilled mirror method when the sample comes into equilibrium with vapor. For WP4C, the samples were taken from two to three different locations within the sample. That includes the top, mid, and bottom and put into the sampling ring of known weight. Usually, the sampling ring was filled up to two thirds of the height, making sure that the samples are within the ring or not overfilled. Then the weight of the ring was taken again with the sample in it. Finally, it was placed inside the sample drawer and the test started. The process was continued at various intervals until the sample started producing a consistent value.

Figure 4.12 WP4c sample test setup

Results. The analyzed data from soil 1 and soil 2 illustrate that most of the biochar is able to retain moisture more than the soil sample. Also, the difference at 3% as well as 6% was observed with both soil when the data were compared at 100 kPa, which can be seen on Figure 4.13. The 100 kPa reference points chosen from previous research indicate the water potential of the environment. Most of the biochar exhibited higher water retention at 6% than the 3% biochar content.

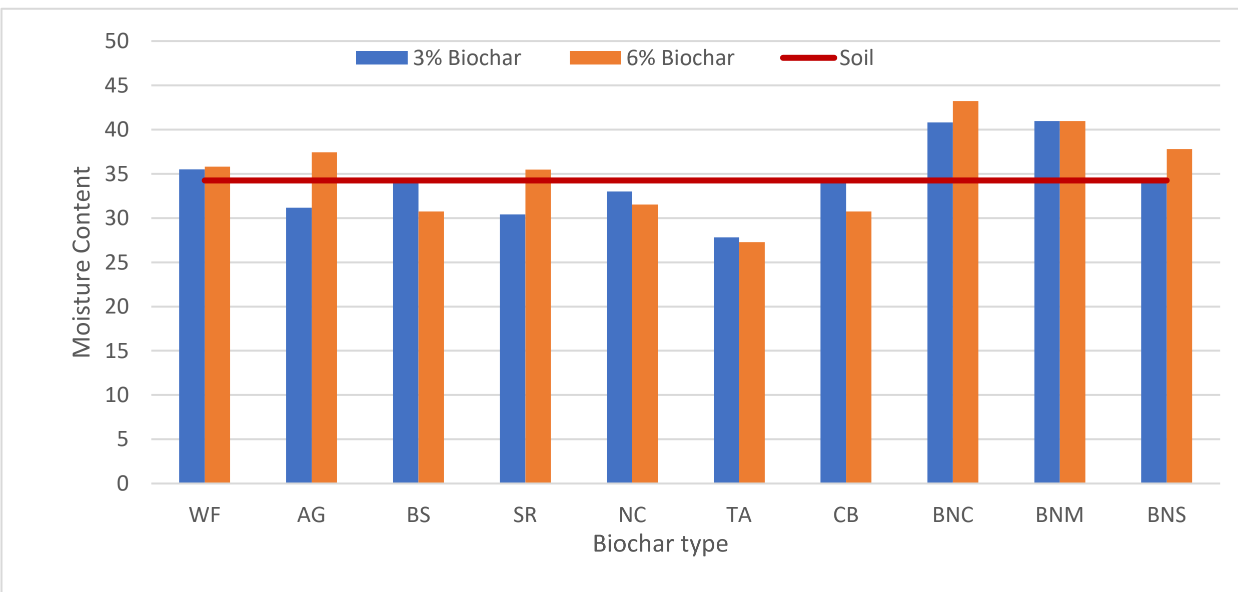

Figure 4.13 Water retention capacity of the biochar with Soil 1 mixtures at 3% and 6% biochar content.

All the biochar with Soil 2, show the higher difference in water retention capacity at both the biochar percent in the samples. The difference in biochar content is illustrated in Figure 4.13 and Figure 4.14 at 100 kPa. This variance with Soil 1 was not that high because it has higher organic content than Soil 2. Blue Sky, Aries Green, Biochar Now Small, and Biochar Now Medium were the top performers with both soils and Anderson was the least of the performers.

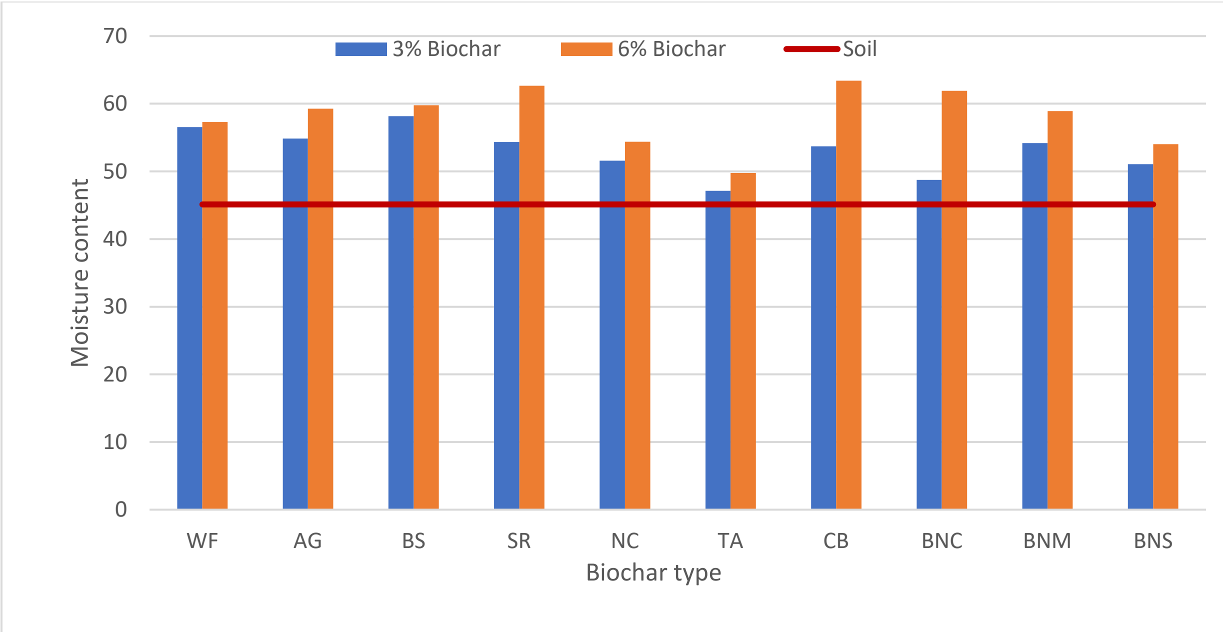

Figure 4.14 Water retention capacity of the biochar with Soil 1 mixtures at 3% and 6% biochar content.

Conclusion. The results from saturated hydraulic conductivity show that most of the biochar shows improved efficiency with both soils. It has also been observed that the size of the soil also has a significant effect on the Ksat capacity. Soil 1 had comparatively larger particle size which is reflected in the result where it shows higher infiltration capacity than Soil 2. The analyzed data from HYPROP + WP4C shows most of the biochar have higher water retention capacity than the control samples. Also, increasing the biochar content from 3% to 6% also increases the moisture retention capacity of the samples.

4.3 Summary of Findings

The physicochemical properties of biochar show that each biochar has a different particle size, dry bulk density, and pycnometer density. This results in different porosity and void ratio between the biochar soil mixtures. The higher porosity of the biochar helps in improved saturated hydraulic conductivity. Also, the biochar can have higher moisture content than the soil sample only, which was found through HYPROP + WP4C testing. The higher surface area of biochar helps in the contaminant's removal and Methylene blue adsorption capacity of the biochar shows that most of the biochar has a higher surface area.

- Through the different physicochemical characterization, it has been found that each biochar has different particle size, dry bulk density, and specific gravity. Because biochar is very porous and has comparatively larger size than soil which results in different and enhanced porosity when mixed with soil. BS, SR, and CN biochar shows the highest porosity with both soils. BNC with soil 1 and BNM with soil 2 showed the least effect on porosity.
- Most of the biochar showed significant Methylene blue adsorption capacity at 25 and 50 mg/l. Whereas, the lower adsorption capacity was not significant at higher concentrations of 100 and 250 mg/l. WF, BS, SR, and CB were top performers; BNM and BNM showed the lowest adsorption capacity.
- Heavy metals could be present in soil as well as biochar. This study shows that aluminum, magnesium, and manganese are present in very high content in all the biochar and soil samples. Also, the soil samples show the higher presence of almost all the analyzed heavy metals.

- Due to improved porosity, most of the biochar showed higher saturated hydraulic conductivity. SR, CB, BNM, and BNS mixture samples showed comparatively higher infiltration capacity with both soils. BS, CB, SR, and BNM showed the higher water retention capacity whereas TA was the lowest performer with both soils.
- Overall, higher percentages of the biochar indicate better performance. This study found that 6% biochar content by the weight of the soil showed higher efficiencies.

5. BIOCHAR AMENDMENT IMPACT TO STORMWATER QUALITY

5.1 Overview In this section, the removal efficiency of contaminants using various types of biochar was evaluated. Batch testing was conducted to determine the removal efficiency of contaminants at two different biochar content levels: 3% and 6% by weight of the soil. Based on the results of batch testing, six biochar materials exhibiting the highest removal efficiency were selected for further investigation in a long-term column study. Throughout the course of one year, the column effluents were analyzed at nine different time intervals to assess the performance of the selected biochar materials.

5.2 Methods for Contaminant Analysis

The target contaminants including nutrients, indicator bacteria, and heavy metals were analyzed by following the standard methods as listed in Table 5.1.

Table 5.1 Analytical methods used for the contaminants analysis.

Parameters	Instruments used	Standard Method	Comments
pH	Fisher brand Accumet AR15 pH/mV/ °C meter with a pH electrode	/	/
Nutrients	HACH DR2800 spectrophotometer	HACH method 8190 (an approved alternative to standard methods 4500 - PE)	Phosphate, Ammonia, Nitrate and Nitrite
Anions	Dionex ICS-3000 Ion Chromatography with an AS22 Ionpac exchange column	EPA Method 300.1	Nitrate and Nitrite
Indicator Bacteria	Colilert-18 and Enterolert testing kits, IDEXX quantity trays	Standard method 9223B and ASTM method D6503-99	Total coliform, fecal coliform, *Enterococci* and *E. coli*
Heavy Metals	Agilent 5100 inductively coupled plasma-optical emission spectrometry (ICP-OES)	EPA method 200.7	Al, Cu, Cr, Zn, Pb, Mg, and Mn

5.2.1 Nutrients

A suite of nutrients, including total phosphorus, ammonia, nitrate, and nitrite samples were tested for all influent and effluent samples using DR2800 spectrophotometer and Hach kits. The standard protocol from the manufacturer was followed which is based on EPA guidelines for analyzing phosphate, ammonia, nitrate, and nitrite. All the samples were tested in duplicate. Table 5.1 details the standard methods used for nutrients and all other target contaminants, including nutrients, indicator bacteria, and heavy metals.

Figure 5.1 Nutrients testing with HACH kits setup

5.2.2 Heavy Metals

Heavy metals (Copper (Cu), Aluminum (Al), Chromium (Cr), Magnesium (Mg), Manganese (Mn), Lead (Pb), and Zinc (Zn) were analyzed by using Inductively coupled plasma optical emission spectroscopy (ICP-OES). Calibration was performed utilizing Agilent standards purchased for each heavy metal. Ultra-pure water was used with two percent nitric acid for preparing the standards. The heavy metals samples were diluted in 2% nitric acid after filtering with 0.45 um filter paper. Nitric acid is used to dissolve the metals completely in the sample. Next, the samples were stored at $4^{o}C$ until further analysis. All the tests were done in triplicate. ICP-OES instrument setup was done according to Agilent guidelines and the laboratory's standard operating procedures based on EPA method 200.7. Quality control consisted of testing performed within six standards to produce standard curve and a blank sample for monitoring instrument performance. The observed concentrations for each element were calculated based on the standard curve plotted intensities.

Figure 5.2 ICP-OES setup for heavy metals analysis

5.2.3 Indicator Bacteria

Indicator bacteria testing was conducted within 48 hours after the filtration of the samples by using IDEXX testing kits (Colilert-18 and Enterolert) to analyze the total coliform, fecal coliform, *Enterococci*, and *E. coli* levels. The testing was conducted using the IDEXX quantity-trays. Standard testing protocol was followed as per manufacturer's guidelines which is based on ASTM D6503-99 and standard method 9223B. 100 ml filtered out samples were taken into 100 ml sterilized plastic cups. Extreme care was taken to avoid contamination and positive wells were counted for the analysis. All the testing was done in duplicate.

5.3 Batch-Testing


Figure 5.3 IDEXX test setup

5.3.1 Method for Batch-Test Simulation

Removal of nutrients, heavy metals, and indicator bacteria from the stormwater were analyzed through batch testing for all the ten biochar with two different clay soil. This test was used as a fast-screening test to finalize the six best performing biochar for the column study. Two different ratios of biochar 3% and 6% by the weight of the soil were decided for batch testing based on the available literature, cost-effectiveness, and practical applicability. A total of 44, 1-liter glass bottles were washed, autoclaved, and prepared for testing. This includes stormwater only, soil only (control), and ten biochar at two different ratios with two replications. A ratio of 100:1 was used for the stormwater to the biochar soil mixture for the testing. A four-week seeding period was adopted for the generation of biofilm. Initially, the mixture was placed in the beaker with 15ml stormwater. Then, 3ml stormwater was added every third day for the biofilm generation over the period of four weeks to keep the media in a wet condition. The total added amount of stormwater was 39ml based on the required amount of stormwater for testing which is 600ml. After the seeding period, the 541ml of remaining stormwater was added to the beaker and placed on the shaker at 180 rpm for 24 hours. Finally, the samples were filtered through 0.8um filter paper for the indicator bacteria testing whereas for the nutrients and heavy metals the samples were filtered through 0.45um filter paper. All the samples were tested within 48 hours after the filtration. The samples for heavy metals were stored at 4C with 2% nitric acid for further analysis.

$$\text{Percent Removal} = \frac{\text{Effluent concentration (soil)} - \text{Effluent concentration (media)}}{\text{Effluent concentration (soil)}} * 100$$

Equation 8

Figure 5.4 Batch testing setup

5.3.2 Results

After filtration, all the effluents were tested for nutrients, indicator bacteria, and heavy metals with both soils. It has been found that most of the biochar comparatively had better performance than control sample (soil only). **T**est results for the nutrients shown in Table 5.1 illustrate that biochar could be effective media for the treatment. Wakefield, Blue Sky, Naked Char, Char Bliss, Biochar Now Medium, and Biochar Now Small showed promising results. Due to very high stormwater to biochar soil mixture ratio during the batch testing resulted in less quantity of biochar for the whole volume. And in the stormwater biochar soil mixture matrix, possibly soil would have significant influence in the removal process. The obtained data showed that some biochar have added up to 50% more removal efficiency of phosphate than the control samples for both the soil. A similar kind of performance was observed for the ammonia removal. The performance of biochar was consistent for the removal of nitrate and nitrite with both soils where the same trend in the removal efficiency was found.

Indicator bacteria testing also showed promising results (see Table 5.3). Top performing biochar were Wakefield, Aries green, Soil Reef, Naked Char, Char bliss, Biochar Now Medium, and Biochar Now Small. The total coliform result shows that the biochar soil mixture has the added benefit of up to 90% with both biochar soil mixture. However, all the samples were tested after filtration with 0.45 um filter paper. that would have intercepted the bacteria on its surface. Because of the interception, the obtained result did not show any presence of E. coli, Fecal coliform, or Enterococci. Because of that, for the batch testing with the second soil, the testing was done for 6% biochar only. As expected, no positive results were found for E. coli, Fecal coliform, or Enterococci. For total coliform, most of the biochar showed limited removal efficiency.

Table 5.2 Nutrients removal by different biochar at 3% and 6% biochar content with both soils

Biochar Type	Biochar Mix (%)	Soil 1				Soil 2			
		Phosphate	Ammonia	Nitrate	Nitrite	Phosphate	Ammonia	Nitrate	Nitrite
WF	3%	-63%	32%	23%	-14%	-60%	-30%	38%	34%
	6%	-136%	46%	20%	-43%	27%	36%	42%	41%
AG	3%	56%	26%	8%	-57%	42%	-34%	-4%	36%
	6%	22%	54%	3%	29%	52%	22%	-12%	45%
BS	3%	-95%	20%	21%	36%	42%	38%	39%	45%
	6%	-209%	23%	35%	43%	50%	13%	48%	45%
SR	3%	-154%	49%	13%	-64%	53%	36%	-30%	30%
	6%	-111%	44%	31%	-14%	29%	40%	-5%	48%
NC	3%	32%	-3%	-5%	-71%	42%	30%	24%	32%
	6%	-5%	26%	16%	57%	-7%	-9%	43%	36%
TA	3%	50%	19%	-154%	-5557%	10%	46%	-65%	-266%
	6%	24%	-2%	-156%	-11893%	-31%	-1%	-85%	-477%
CB	3%	-78%	59%	21%	93%	31%	36%	37%	45%
	6%	-75%	35%	24%	93%	41%	22%	42%	55%
BNC	3%	39%	-44%	6%	79%	-5%	36%	-12%	11%
	6%	45%	66%	18%	86%	-25%	-46%	1%	7%
BNM	3%	65%	-136%	11%	86%	1%	-7%	-36%	48%
	6%	56%	-25%	24%	86%	-7%	26%	-8%	55%
BNS	3%	44%	-1%	8%	86%	8%	13%	-57%	52%
	6%	27%	44%	17%	71%	25%	-9%	-9%	57%

Table 5.3 Indicator bacteria removal by different biochar at 3% and 6% biochar content with Soil 1.

Biochar mixed with soil	Biochar percentage	Total coliform MPN read (per 100ml)
Control (Soil only)	0	9
WF	3%	4.2
	6%	4.7
AG	3%	1670.2
	6%	2.0
BS	3%	3.6
	6%	1986.35
SR	3%	0
	6%	0
NC	3%	0
	6%	0
TA	3%	311.9
	6%	78.85
CB	3%	4.2
	6%	4.3
BNC	3%	6.3
	6%	2.1
BNM	3%	5.2
	6%	2.1
BNS	3%	5.2
	6%	3.6

* MPN number less than 1 is used as 0 for the analysis of indicator bacteria. *E. coli*, fecal coliform and *Enterococci* values were less than 1 for all samples (so not included in the table).

The heavy metal results from the batch testing with both soils are shown in Table 5.4 at 3% and 6% biochar content. It has been found that the biochar soil mixture of Wakefield, Blue Sky, Soil Reef, Naked Char, Char Bliss, and Biochar Now Medium could efficiently remove the target metals including Al, Cu, Cr, Zn, Pb, and Mn with Soil 1. The same trend for the removal was seen with Soil 2. As higher amounts of heavy metals were found during the physiochemical characterization from the biochar and soil samples, this potentially would have interfered with the removal efficiency.

Table 5.4 Heavy metals removal by different biochar at 3% and 6% biochar content with both soils.

Biochar Type	Biochar Mix (%)	Soil 1							Soil 2						
		Al	*Cu*	*Cr*	*Zn*	*Mn*	*Pb*	*Mg*	*Al*	*Cu*	*Cr*	*Zn*	*Mn*	*Pb*	*Mg*
WF	**3%**	6%	9%	-21%	-74%	39%	1%	-10%	173%	-60%	-1%	21%	5%	8%	33%
	6%	-92%	20%	-21%	-75%	67%	5%	-14%	133%	2%	65%	89%	79%	-16%	-8%
AG	**3%**	-93%	-8%	10%	-76%	-90%	-2%	-2%	106%	-83%	25%	26%	28%	22%	49%
	6%	-89%	15%	-8%	47%	78%	15%	3%	113%	8%	33%	81%	79%	-13%	27%
BS	**3%**	-103%	20%	14%	49%	-59%	43%	-3%	9%	25%	40%	93%	52%	12%	-2%
	6%	32%	2%	-12%	-1%	88%	69%	3%	-7%	42%	7%	96%	74%	-20%	-36%
SR	**3%**	-117%	24%	-9%	33%	83%	31%	2%	8%	39%	1%	86%	79%	-2%	-42%
	6%	-51%	64%	-20%	32%	86%	-13%	4%	48%	30%	51%	80%	93%	4%	-36%
NC	**3%**	-66%	-30%	-25%	13%	73%	10%	-12%	32%	20%	53%	83%	83%	13%	-72%
	6%	-41%	24%	17%	30%	83%	23%	-19%	29%	22%	41%	94%	82%	-6%	-89%
TA	**3%**	-117%	-8%	-29%	-55%	0%	75%	-76%	41%	2%	17%	89%	0%	-29%	-50%
	6%	-83%	-46%	7%	47%	0%	-14%	-88%	0%	-65%	48%	10%	0%	47%	-124%
CB	**3%**	22%	34%	-5%	75%	42%	4%	-5%	19%	-1%	27%	-129%	77%	-23%	0%
	6%	30%	14%	-4%	52%	82%	-8%	5%	74%	44%	33%	67%	75%	-26%	22%
BNC	**3%**	21%	-17%	-13%	54%	87%	31%	-4%	13%	47%	29%	48%	17%	27%	3%
	6%	34%	36%	-6%	47%	78%	-14%	8%	125%	-66%	10%	1%	-36%	33%	33%
BNM	**3%**	26%	28%	4%	74%	90%	26%	-2%	141%	-25%	8%	72%	-18%	0%	10%
	6%	28%	6%	-27%	60%	89%	5%	-8%	63%	-1%	-37%	91%	31%	14%	12%
BNS	**3%**	10%	12%	-13%	51%	79%	-8%	-2%	67%	12%	34%	63%	75%	-30%	-14%
	6%	34%	36%	16%	73%	87%	-15%	-7%	68%	6%	8%	75%	75%	27%	-16%

5.3.3 Conclusion

The batch testing results with all the ten biochar and both the soil shows variation in the results for nutrients, indicator bacteria and heavy metals. Most of the biochar shows good removal efficiency for phosphate, ammonia, nitrate, and nitrite. Similarly, the result was observed for total coliform removal. However, during the filtration process, filter paper intercepted the bacterial concentration. Thus, the obtained result shows lower effluent concentration for fecal coliform, *E. coli*, and *Enterococci*. Heavy metals variation in the performance was observed especially at 3% biochar content and biochar and soil could possibly have added heavy metals. However, 6% biochar comparison shows better removal efficiency but still in the lower range except with few biochar.

5.4 Column-Testing

5.4.1 Column Setup Methodology

Six best performing biochar from the preliminary testing were selected for the column testing. The selection of biochar was based on the performance from batch testing and saturated conductivity with biochar soil mixture at two different percentages of biochar at 3% and 6% by the weight of the soil. The performance of biochar for methylene blue adsorption capacity and porosity were also taken into consideration for deciding biochar type and percentage for the column study. Eight columns have been installed which consist of one control (Soil only), Wake Field, Blue Sky, Soil Reef, Naked Char, Char Bliss, Biochar Now Medium, and Biochar Now Small. The concentrations of biochar in all the columns were 6% by the weight of the soil except Biochar Now Small with 3%.

Table 5.5 Composition of biochar for each column

Column no.	Column type	Biochar composition
Column 1	Soil only	0%
Column 2	Wake Field	6%
Column 3	Blue Sky	6%
Column 4	Naked Char	6%
Column 5	Char Bliss	6%
Column 6	Biochar Now Medium	6%
Column 7	Biochar Now Small	6%
Column 8	Biochar Now Small	3%

The column bench was built in the lab and clear PVC columns set up were installed into that. The column has an inner diameter of 3 in and a total length of 60 in. The column preparation was done by following the study of Ghavanloughajar et al. (2020). Where the PVC column setup included a 3-inch reducer, 1.5-inch connector, and 1.5-inch pipe. A double layer of screen wire mesh was glued to the bottom reducer, and a 6-inch layer of pea gravel was added at the base. Biochar and soil mixture were poured into the column in three layers, compacted at specific heights. Flow rates were tested after saturation. A top layer of pea gravel prevented biochar from mixing with water. The columns were retested to ensure desired flow rates of 1-3 inches per hour. The setup aimed to create efficient filtration while maintaining consistent water flow.

Figure 5.5 Mixing, filling, and compacting for the column setup.

Column Seeding. After maintaining the flow rate, the columns were seeded for four weeks to generate the biofilm within the column, as it was done for batch testing. During the seeding time, the flow rates were checked again at the end of the second and fourth weeks. It was found that the flow rate of two columns was above the recommended range. The potential reason for this could be that the columns were not fully saturated as the seeding volume of columns were only one liter. Finally, before starting the first column test, the flow rates were checked again and found to be in the range for all the columns. The measured flow rate on the day of testing was as low as 1in/hr for BNS 3% to as high as 3 in/hr for the soil column. However, the flow rate for all the columns were in the range which are summarized in Table 5.6 for all the columns.

Figure 5.6 Filtration column setup.

Column Infiltration Rate. Infiltration rates for each column were measured at different periods throughout the project. Table 5.6 summarizes the flow rate for each time interval. It has been found that up to fifteen weeks of seeding the column, the infiltration rate was still within the limit of 1 in/hr. However, over the time, most of the columns showed reduced filtration capacity and after almost a year most the of the biochar column showed reduced infiltrating capacity. The measured infiltration capacity for all the columns was less than 1 in/hr. Biochar Now Small 3% column showed the lowest infiltration capacity.

Table 5.6 Infiltration rate of the columns measured by gravity filtration for the project at different time interval across the year.

Column no.	Biochar compositio n	Initial ±0.1 in/hr (May 05, 2022)	Six Weeks of Seeding (June 17, 2022)	Ten Weeks of Seeding, ±0.1 in/hr (July 25, 2022)	Fifteen Weeks of Seeding (Aug 30, 2022)	Final (April 30, 2023)
Column 1	Soil only	2.4	2.8	> 1 in/hr (Ok)	> 1 in/hr (Ok)	<1 in/hr (Partially clogged)
Column 2	Wake Field	2.8	1.4	> 1 in/hr (Ok)	> 1 in/hr (Ok)	<1 in/hr (Partially clogged)
Column 3	Blue Sky	1.7	2.3	> 1 in/hr (Ok)	> 1 in/hr (Ok)	<1 in/hr (Partially clogged)
Column 4	Naked Char	1.9	1.6	> 1 in/hr (Ok)	> 1 in/hr (Ok)	<1 in/hr (Partially clogged)
Column 5	Char Bliss	2.8	1.1	<1 in/hr	<1 in/hr (Partially clogged)	<1 in/hr (Partially clogged)
Column 6	Biochar Now Medium	2.9	2.6	> 1 in/hr (Ok)	> 1 in/hr (Ok)	<1 in/hr (Partially clogged)
Column 7	Biochar Now Small 6%	2.8	2.2	> 1 in/hr (Ok)	> 1 in/hr (Ok)	<1 in/hr (Partially clogged)
Column 8	Biochar Now Small 3%	1.8	1.0	<1 in/hr	<1 in/hr (Partially clogged)	<1 in/hr (almost clogged)

Column Test Runs. Stormwater was introduced to the columns within 48 hours of all the stormwater collection events summarized in Figure 5.8. One liter collected stormwater samples were allowed to filter under the force of gravity. The resulting effluents were collected in sterilized water bottles. The heavy metals samples were filtered with 0.45um filter paper and stored at 4°C with 2% nitric acid for further analysis. The performance of the filter columns was assessed through three baseline runs after one month of seeding, followed by two more testing rounds over the next two months. A ten-week dry period was introduced to mimic a dry weather period and account for potential changes in porosity and microbial growth. Seeding was paused, and four additional testing rounds were conducted after this period. The ninth Column Run marked the completion of the year-long study.

Contaminant Concentrations in Stormwater. The water quality of nine collected samples throughout the project is summarized in Table 5.7. During and after the summertime nutrient concentrations are comparatively high. However, it varied though out different collection intervals. As it can be seen from the table that the bacterial concentrations are also high during the summer period and reduced during the winter and early spring season. The concentration of metals varied at different collection intervals. However, similar seasonal trends were not observed for the heavy metals.

*Table 5.7 Water quality data of stormwater collected for all the column testing. (na - data not available and * results<MDL)*

Collection dates	6/18/2022	7/3/2022	7/25/2022	8/30/2022	9/30/2022	12/14/2022	2/2/2023	3/13/2023	4/30/2023
Phosphate (mg/l)	0.615	0.581	0.492	0.718	1.390	0.701	0.285	0.375	0.280
Ammonia (mg/l)	0.657	0.382	0.573	0.428	0.197	0.114	0.174	0.155	0.125
Nitrate (mg/l)	1.775	1.240	1.520	1.509	0.686	0.913	0.593	0.472	0.620
Nitrite (mg/l)	0.055	0.057	0.050	0.147	0.026	0.048	0.053	0.023	0.031
Total coliform (/100mL)	14164000	983000	56550	17800	1859600	98350	24196	na	24196
***E. coli* (/100mL)**	53000	31000	1500	81.5	690	205	776	na	na
Fecal coliform (/100mL)	82.55	82.55	13920	1095	11145	3730	2172	na	1714.15
***Enterococci* (/100mL)**	61410	13105	3590	2590	61410	4960	1314	na	na
Al (mg/l)	1.062	0.539	0.046	0.059	*0.019	0.060	3.300	0.069	*0.021
Cu (mg/l)	0.019	0.009	0.002	0.040	0.005	0.000	*0.004	*0.106	*1.070
Cr (mg/l)	0.002	0.001	0.001	0.003	0.001	0.000	*0.004	*0.101	*0.080
Zn (mg/l)	0.041	0.022	0.009	0.669	0.023	0.005	0.019	0.025	0.005
Mn (mg/l)	0.100	0.036	0.047	0.024	0.017	0.026	2.698	0.086	0.033
Pb (mg/l)	0.000	*0.005	*0.006	*0.007	0.001	*0.004	0.000	0.004	*0.004
Mg (mg/l)	1.234	1.034	0.495	0.790	0.603	2.300	2.984	3.168	1.766

Sampling Schedule. The stormwater samples have been collected at different time intervals across Column Runs. Each sampling event had different effluent concentrations. And the percentage removal through each column was calculated by the given formula (Equation 9). Percent removal is used to present the results of this study. The soil-only column served as a control. Figure 5.8 displays the full column testing schedule.

$$\text{Percent Removal} = \frac{\text{Effluent concentration (soil)} - \text{Effluent concentration (media)}}{\text{Effluent concentration (soil)}} * 100$$

Equation 9

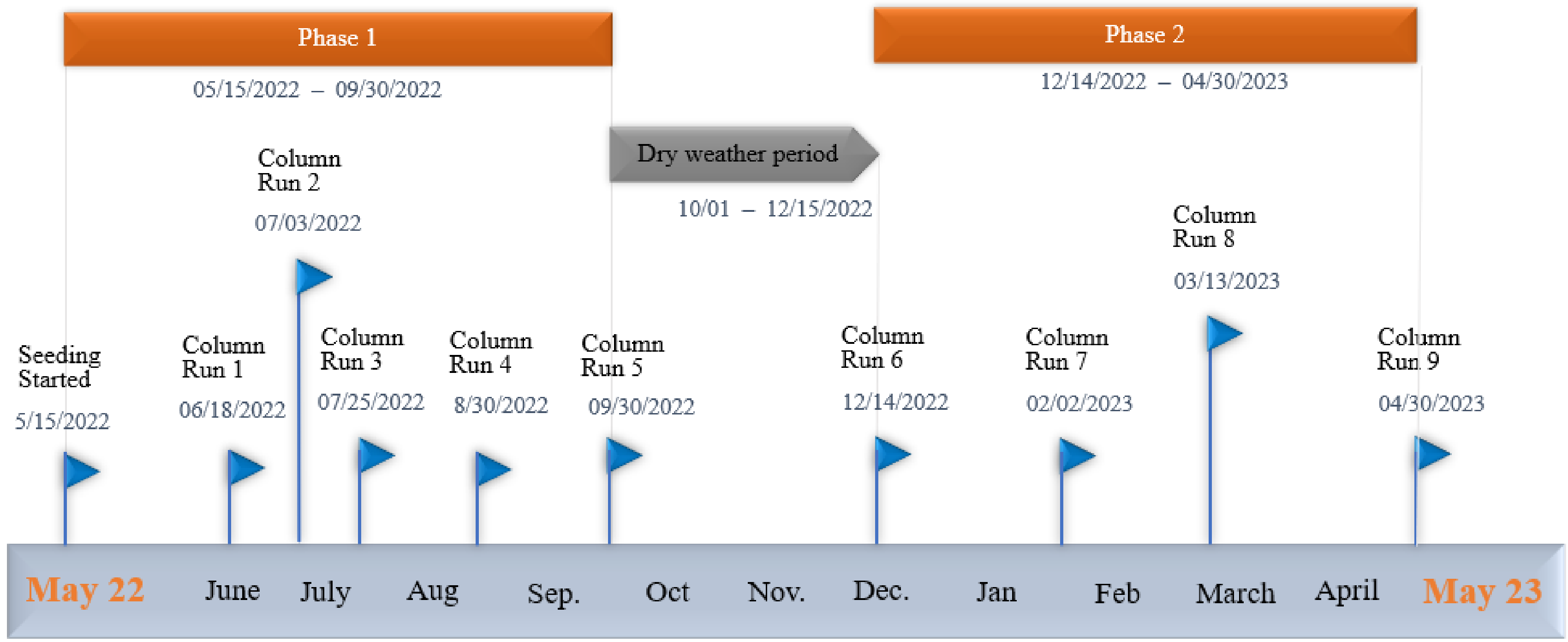

Figure 5.7 Timeline for the column testing

5.4.2 Baseline Results

During the baseline testing, the columns were tested three times biweekly in the span of one month. The columns were seeded with one liter of collected stormwater samples every third day. This process was adopted to mimic the actual environmental conditions of the rain. Also, the processes of biofilm generation were adopted for the column as it was done for the batch testing. To generate the biofilm, the columns need to be in a moisture condition. And seeding the column every third day helped in achieving that process. The process of seeding started in mid-May until mid-June for almost four weeks before starting the first Column Run. In addition, the seeding process was continued during the entire first phase of testing, prior to the dry period.

Nutrient Removal. All the samples were analyzed for phosphate, ammonia, nitrate, and nitrite and the results are shown in Figure 5.8. The result shows that most of the biochar columns were able to effectively remove phosphate from the stormwater except Blue Sky biochar which was not able to add any benefit in comparison to the control column. For the ammonia removal, Biochar Now Medium, Biochar Now Small, and Biochar Now Small 3% columns exhibited the lowest nutrient removals. The highest removal efficiencies with the columns were seen for nitrate removal, all columns showed comparatively very high removal efficiencies. The concentration of nitrite is usually less, and most of the biochar column shows improved performance.

Heavy Metal Removal. All samples were analyzed for Al, Cu, Cr, Zn, Pb, Mn, and Mg. The performance of each column at each testing interval varied (see Figure 5.9). However, most of the columns were able to sufficiently remove most of the heavy metals. Mn and Zn were effectively removed by most of the columns for all the testing events. Moreover, most of the biochar showed effective removal for Al, Cu and Cr. The concentration of Pb was very low for all the testing events, and the result shows variation in the performance at each Column Run. However, the Mg concentration in all the test runs was far higher than the influent concentrations and need only be used for reference. A possible reason for the removal efficiency of the biochar could be initial higher concentrations.

Indicator Bacteria Removal. Indicator bacteria removal performance of the biochar are shown in Figure 5.10. All the samples were analyzed for the total coliform, E. coli, fecal coliform, and Enterococci. Most of the biochar were able to remove sufficiently high amounts of total coliform from the stormwater. Also, from the same positive samples, the observed E. coli concentrations were also comparatively very low compared to the control samples. Fecal coliform bacteria were also significantly removed through most of the biochar except Biochar now medium column. Similarly, performance was also seen for Enterococci removal, where most of the biochar performed significantly better. Biochar Now Medium and Biochar Now Small 6% did not show significant additional removal for all the indicator bacteria.

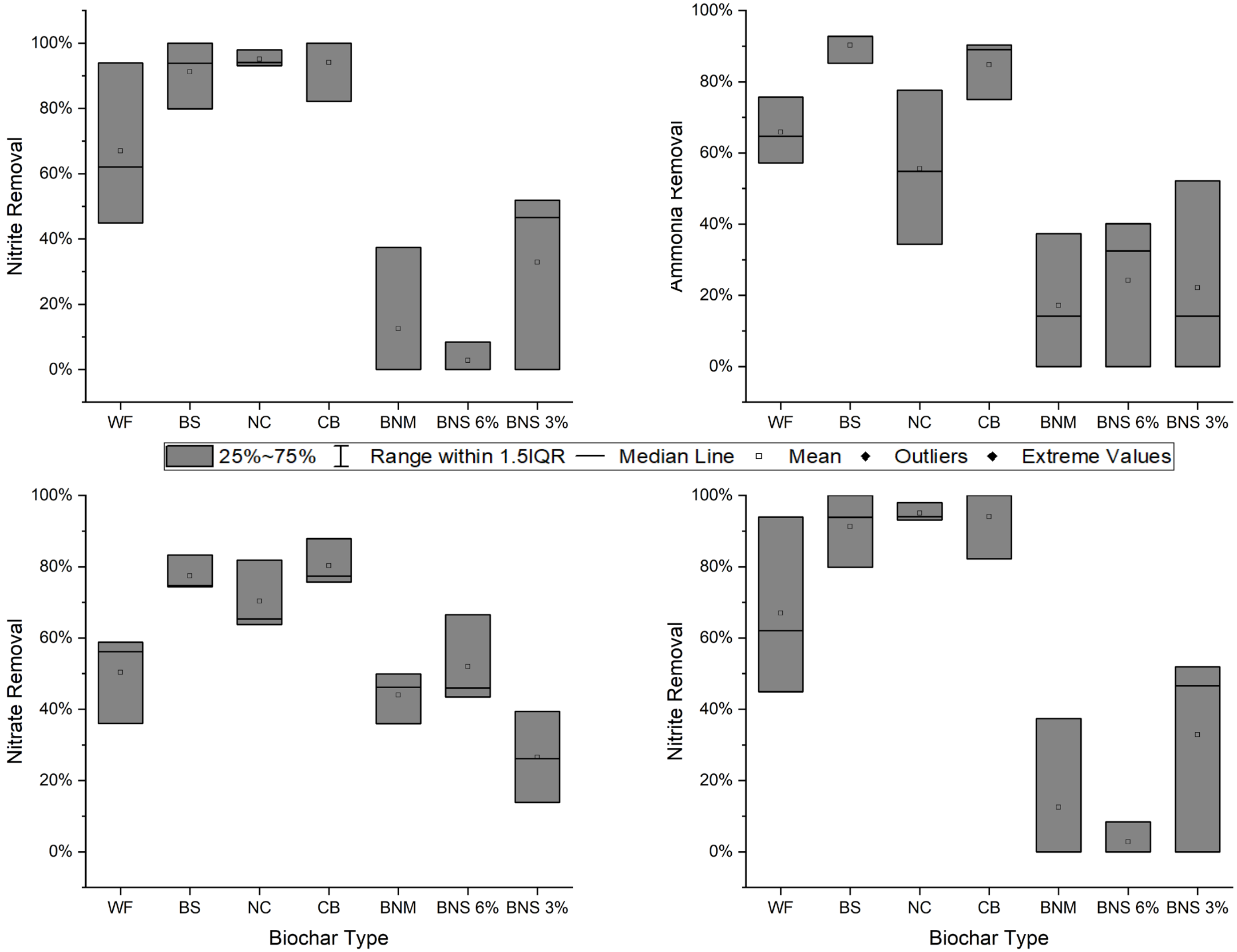

Figure 5.8 Baseline (first three Column Run) results for nutrients removal. Negative values are excluded from the graphs.

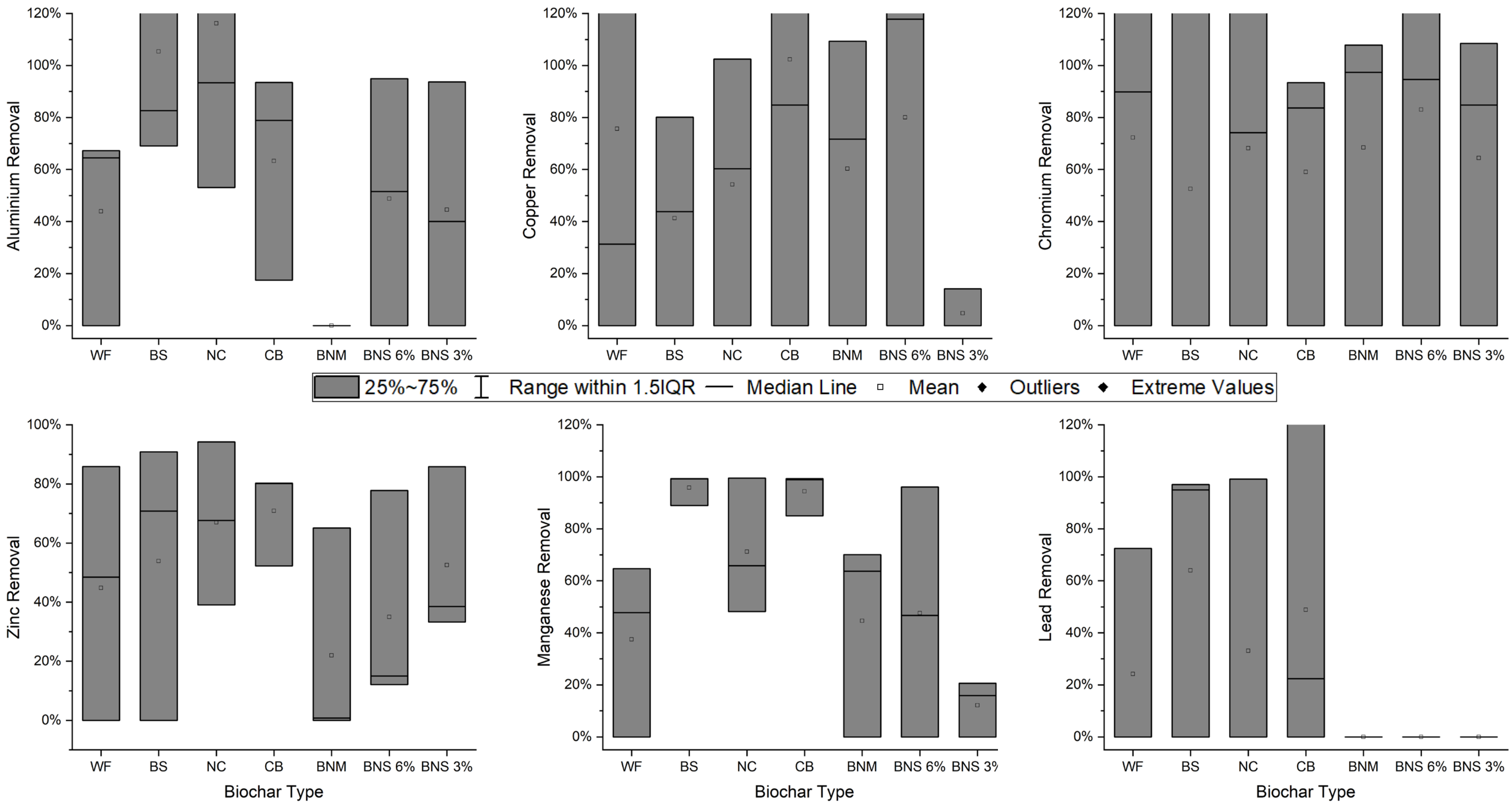

Figure 5.9 Baseline (first three Column Run) results for heavy metals removal.

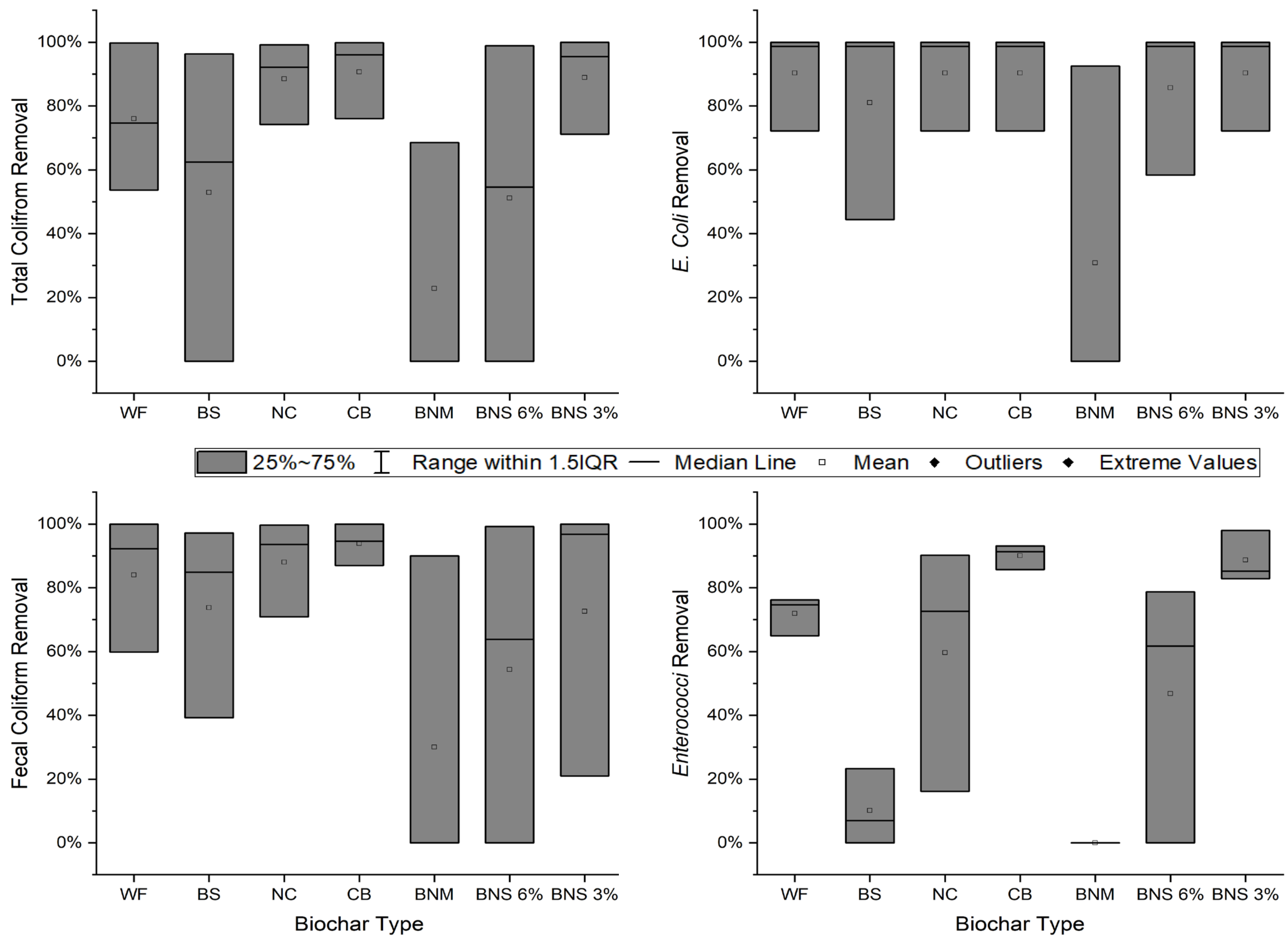

Figure 5.10 Baseline (first three Column Run) results for indicator bacteria removal.

5.4.3 Post- Dry Weather Period Comparative Analysis

This part of the study will evaluate the performance of the columns before and after the drying period. During the dry weather period the columns were allowed to dry at room temperature when the top opening of the columns was left open as well. The dry weather period started right after Column Run 5 starting in October through Mid-December. Following the drying period, the column was sampled an additional four times (Runs 6-9) over a three-month period.

Nutrient Removal. All the samples were comparatively analyzed for phosphate, ammonia, nitrate, and nitrite at before and after drying period and the results are shown in Figure 5.11. From the results a similar trend is observed where the performance of each column is better before the drying period than the performance of the after the drying period. The higher variation in the performance is easily seen in most of the columns during the post dry period. The result shows similar performance for overall nutrients removal which slightly reduced over the time. For the phosphate removal most of the biochar exhibit removal abilities except Sky Blue biochar and Biochar Now Small which had periods of leaching into the effluents. For the ammonia removal, Biochar Now Medium, Biochar Now Small, and Biochar Now Small 3% columns were the least of the performers again where they are not adding much benefit with respect to the soil column. However, the rest of the biochar mixed columns were still able to remove ammonia very well. Again, the best overall removal efficiencies with the columns were seen for nitrate removal. All the columns post-drying still exhibited comparatively high removal efficiencies. The lowest observed removal efficacy was found from Biochar Now Small 6% and Biochar Now Small 3%. The concentration of nitrite is comparatively less, and most of the biochar column shows improved performance during both phases of the testing. Overall, post drying period results show that most of the biochar are still providing the added benefit nutrient removal. However, the performance was reducing over time and some biochar started leaching the nutrients.

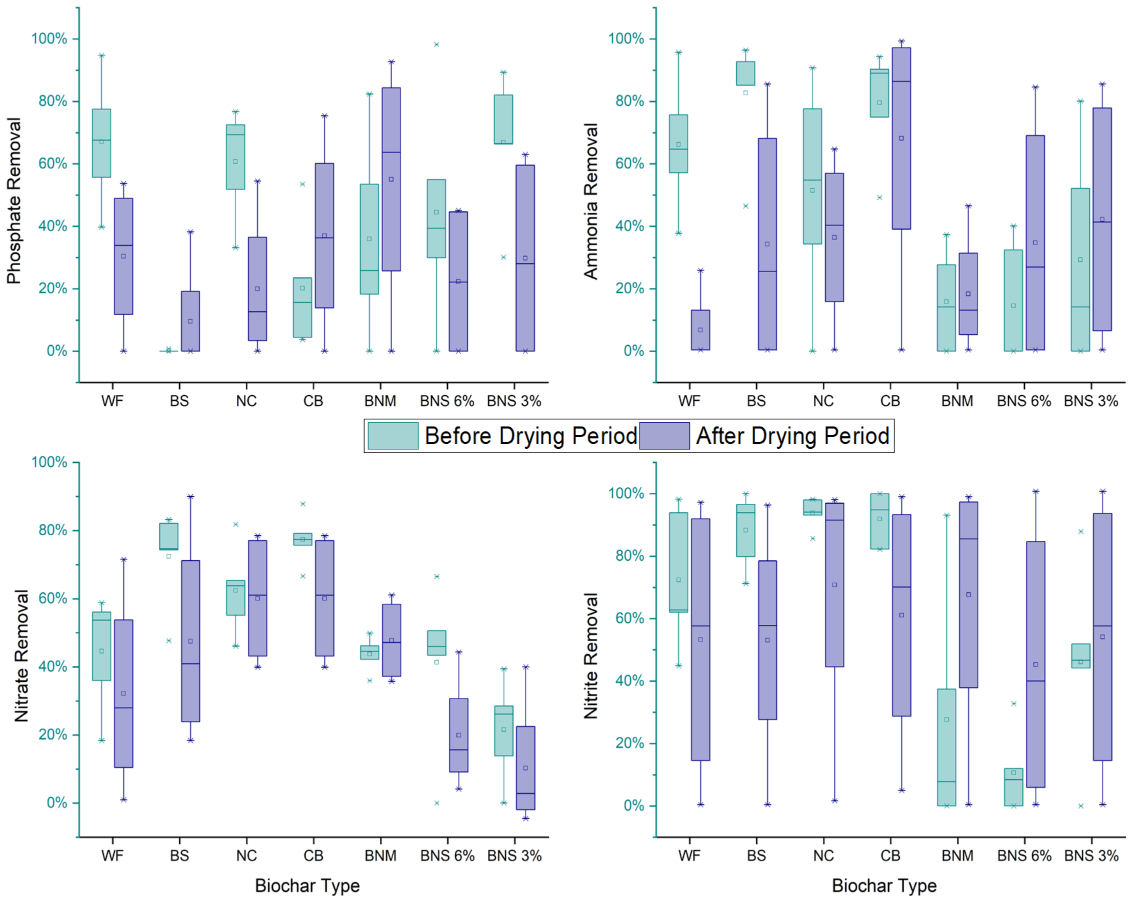

Figure 5.11 Comparative results of before and after drying period for nutrient removal

Heavy Metal Removal. All the samples were analyzed for Al, Cu, Cr, Zn, Pb, Mn, and Mg in this phase as well. The performance of each column at each testing interval varied as it was before which is shown in Figure 5.12. However, most of the columns were able to sufficiently remove most of the heavy metals before and after the drying period. And again, most of the biochar were able to significantly remove Mn and Zn during both phases. For Al, Cu and Cr most of the biochar showed well removal efficiency. The concentration of Pb was very low again for all the testing events and the result shows higher variation in the performance at each column run. However, the Mg concentration in all the test runs were way higher than the influent concentrations which might be because of higher concentrations of heavy metals in biochar and soil, and it should only be used for reference. Overall, from the available results, mixed efficiency for heavy metals could be seen in both the phases and the leaching problem. In addition to that, a reduction in the performance was also observed over the time.

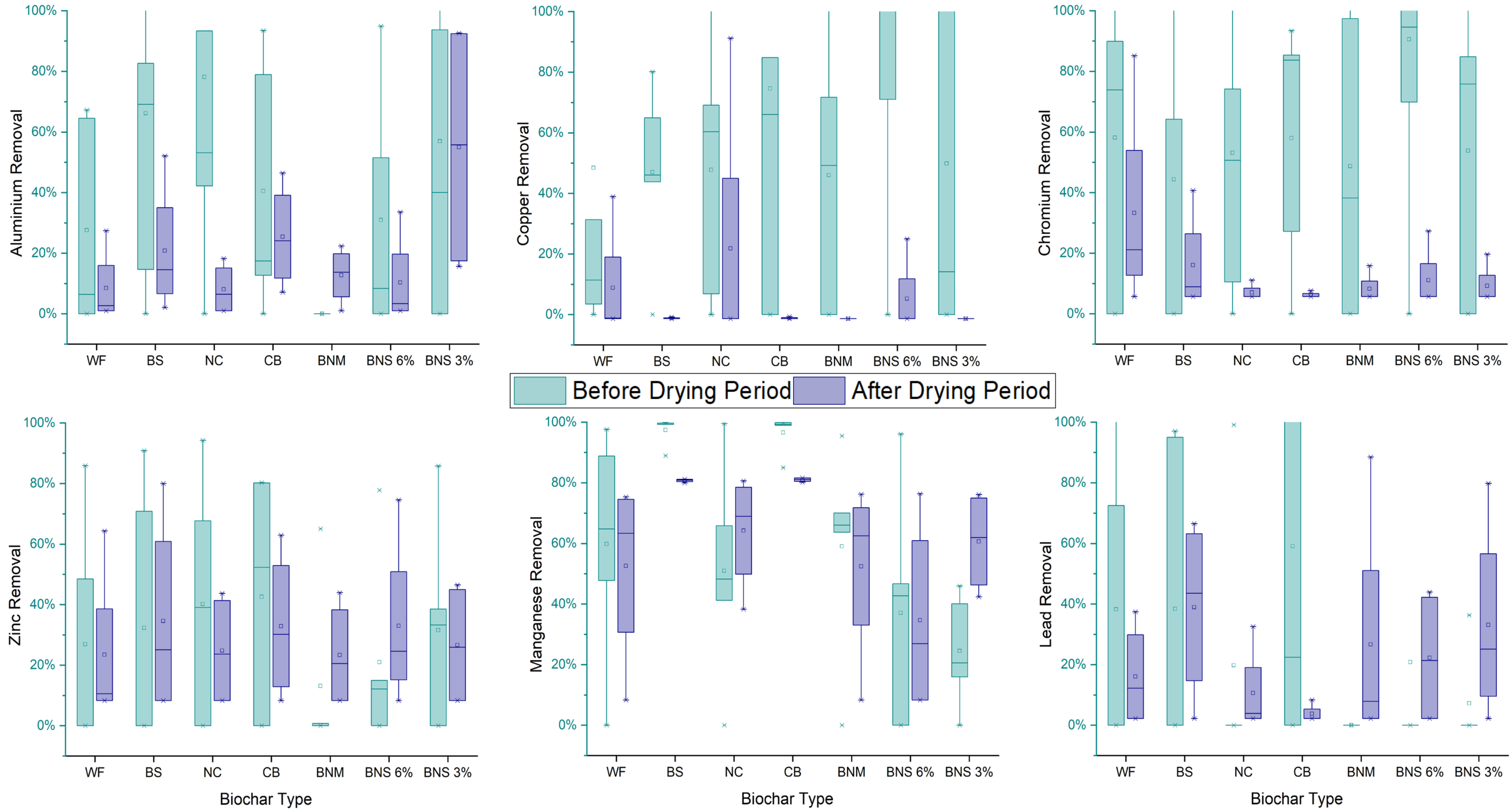

Figure 5. 12 Comparative results of before and after drying period for heavy metals removal

Indicator Bacteria Removal. Similar trends are shown in Figure 5.13 for the bacterial analysis. We must note that bacterial analyses were not completed for Column Runs 8 and 9. Column 8 was added after the beginning of the study to capture nutrient and heavy metal removals. And the florescence light was not working for Column Run 9 E. Coli and enterococci results. Most of the biochar were able to remove sufficiently high amounts of total coliform from the stormwater. Also, from the same positive samples, the observed E. coli concentrations were also comparatively very low in both phases of the testing. Fecal coliform bacteria were also significantly removed through most of the biochar. Comparable performance was also seen for Enterococci removal, where most of the biochar performed significantly better except Biochar Now Small 6% and Biochar Now Small 3%. Both the column Biochar Now Small 6% and Biochar Now Small 3% did not show significant additional improvement for indicator bacteria. Overall, the performance during the post during phase was reduced for most of the biochar however they were still able to add the benefits.

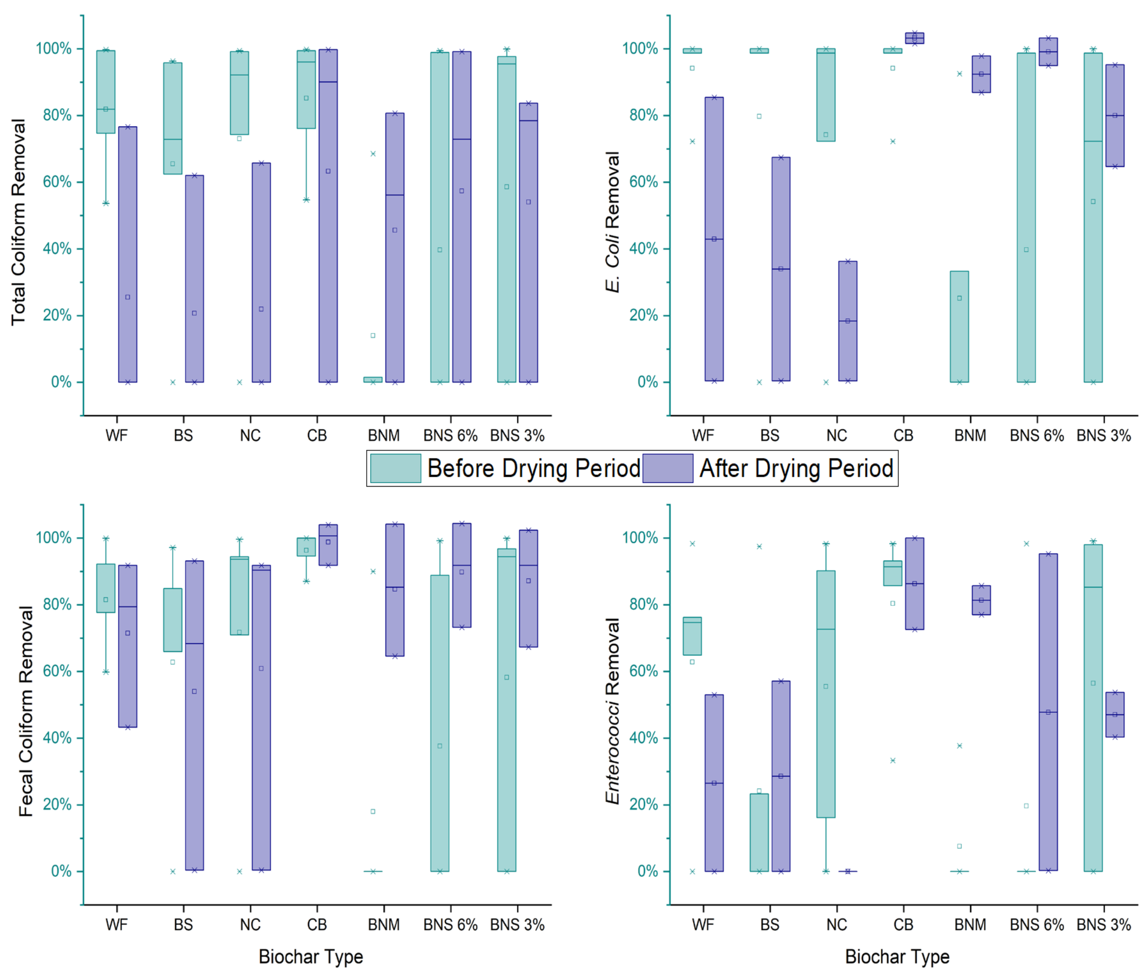

Figure 5.13 Comparative results of before and after drying period for indicator bacteria removal

5.4.4 Long-Term Column Performance (1-Year)

The data were analyzed to find the effect of aging and column performance over the year within each column. For this purpose, baseline data was compared with the last two column runs. The nutrients data showed a slight reduction in the performance of the columns over the year which can be seen Figure 5.14. Results show that Blue Sky biochar is not efficient in phosphate removal. Char Bliss and Naked Char biochar column showed good removal efficiency for all the nutrients. The least performing column was Biochar Now Small. For earlier test runs, the plotted results in Figure 5.15 show that most of the biochar are able to perform very well in regard to heavy metals. However, as expected, the overall performance over the year was reduced. Blue Sky, Char Bliss, and Naked Char biochar columns were the top performers for the removal of most of the heavy metals. Wake Filed and Biochar Now Medium showed the lowest added benefits for most of the heavy metals over the time. Mixed results were observed for indicator bacteria testing which can be seen in Figure 5.16 where some biochar showed comparatively better performance after a year. During certain testing events, some of the samples yielded negative indicator bacteria removals suggesting that bacteria was leaching from the columns. Char Bliss, Biochar Now Medium, and Biochar Now Small biochar column showed the best removal capacity towards indicator bacteria removal. Whereas Wake Field, Blue Sky, and Naked Char biochar columns were most affected over the year.

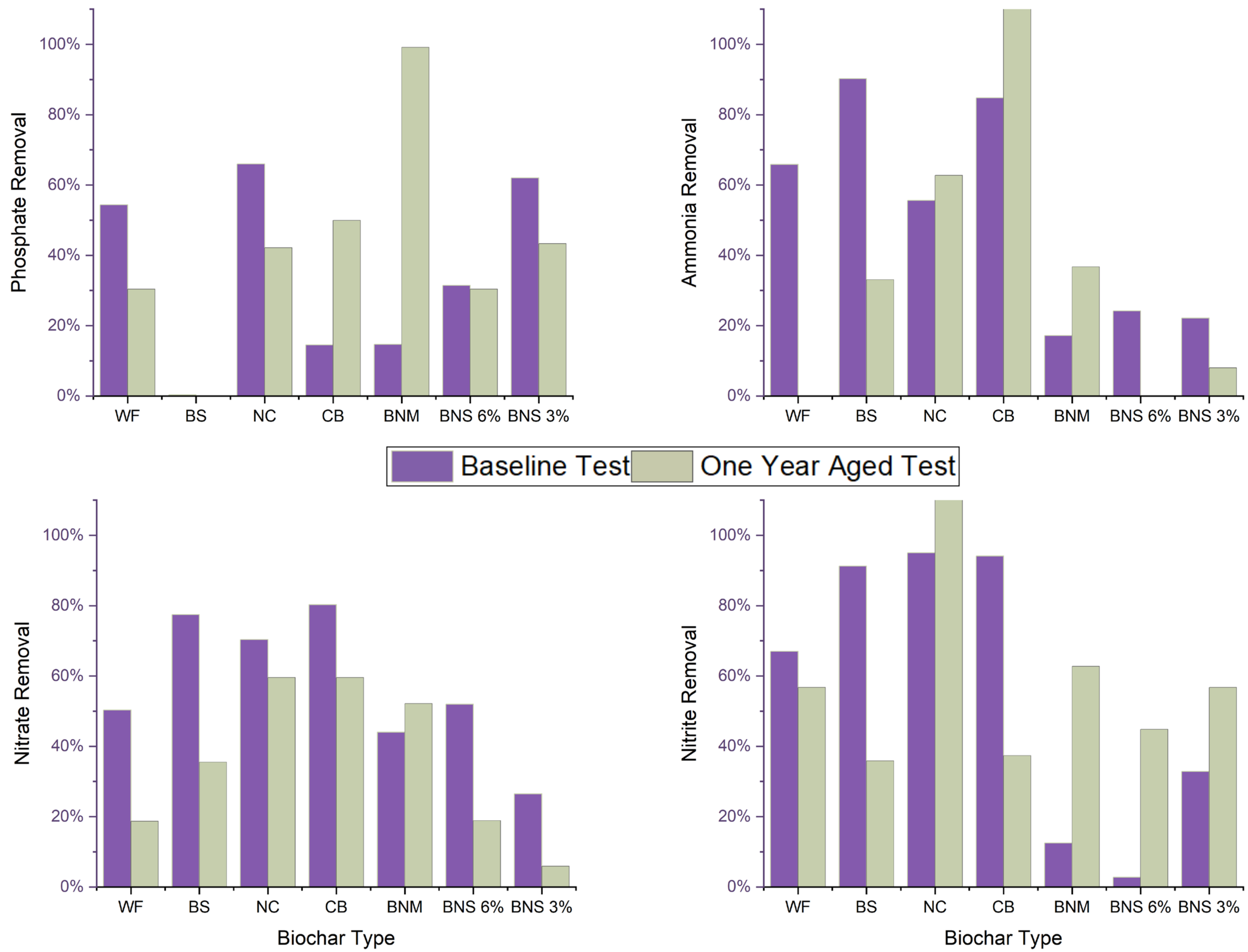

Figure 5.14 Comparative nutrients test result for aged column

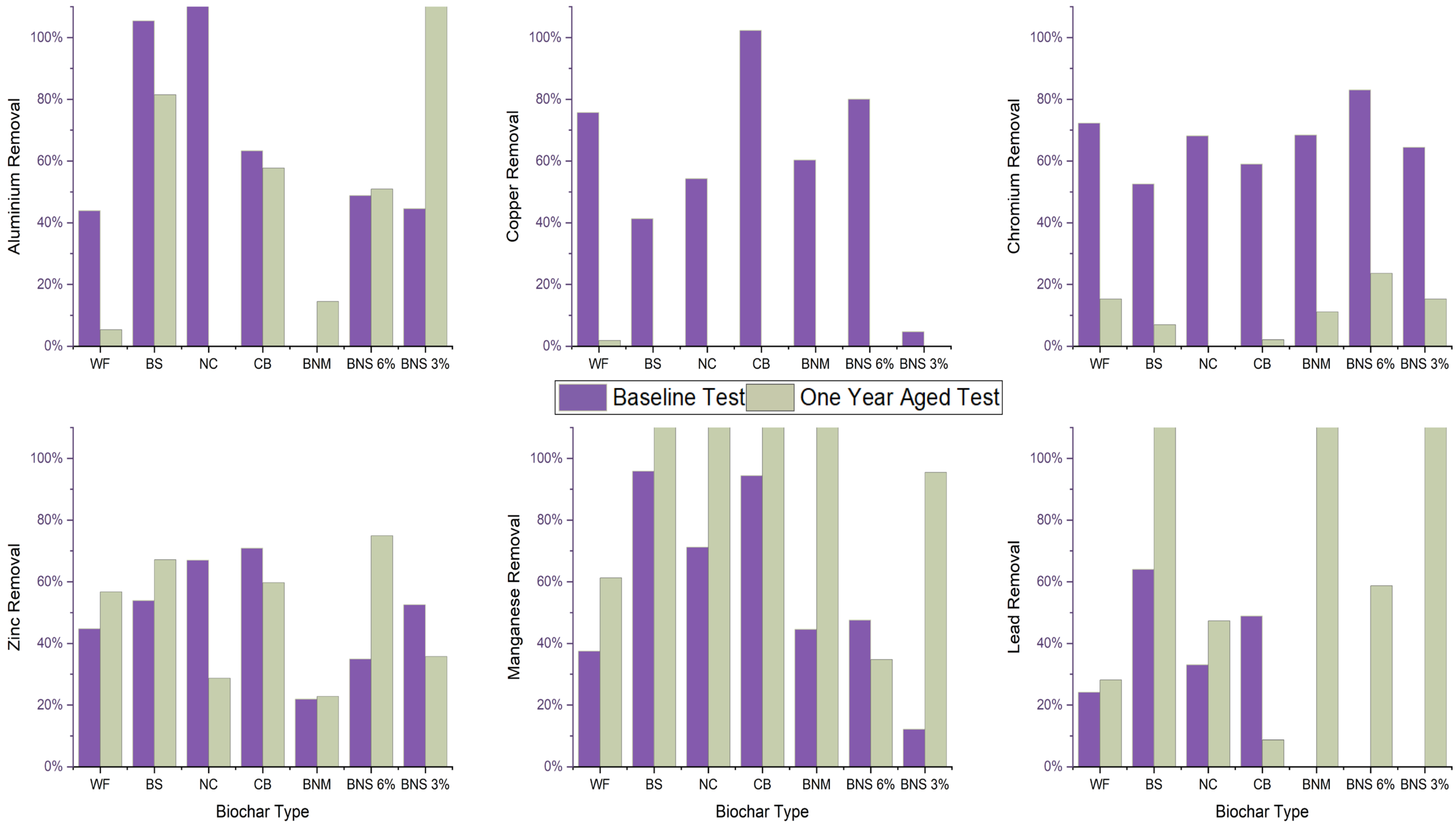

Figure 5.15 Comparative heavy metals results for aged column

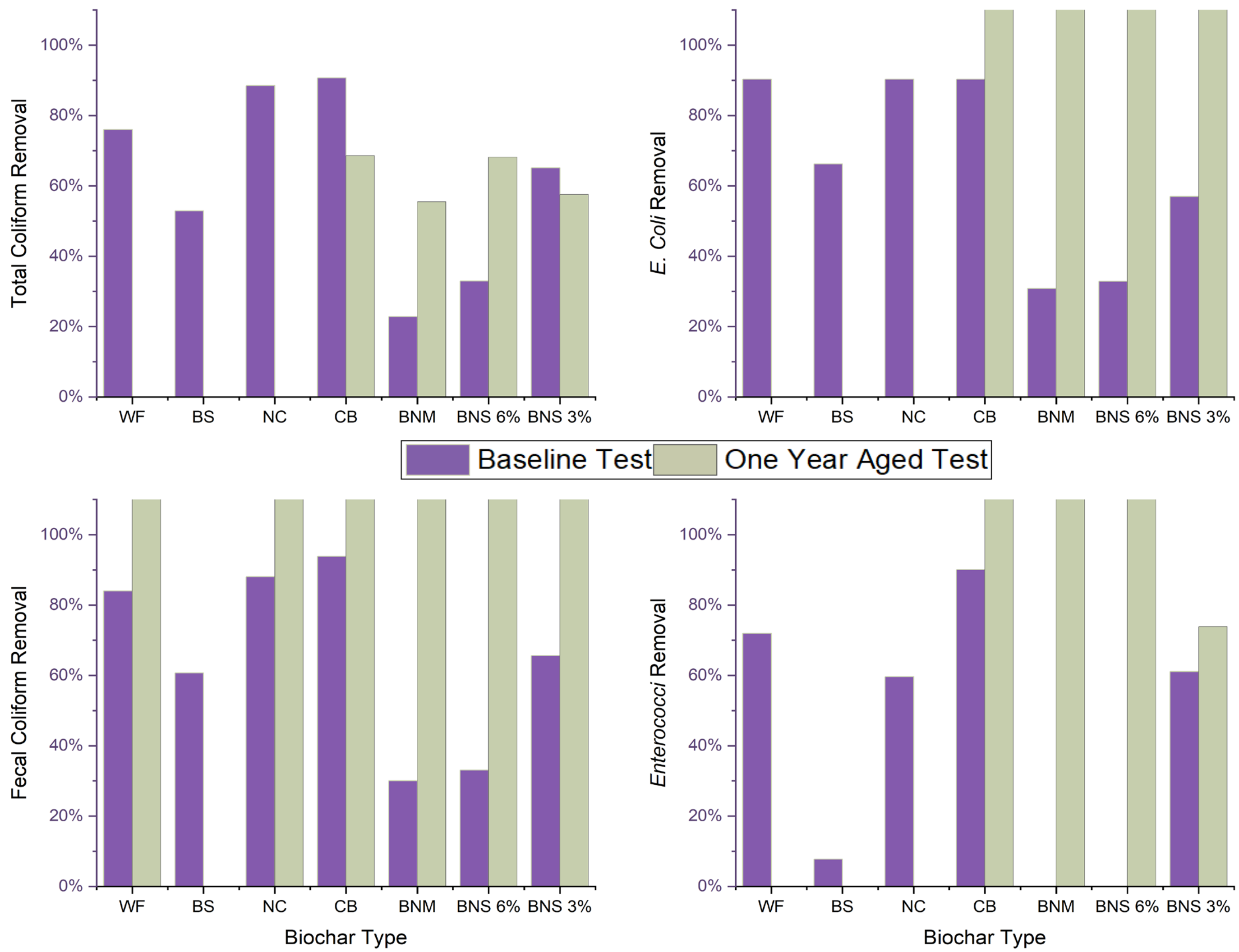

Figure 5.16 Comparative indicator bacteria test result for aged column

5.4.5 Conclusion

Biochar amended soils exhibited the ability to improve water quality by removing relatively more nutrients, heavy metals, and indicator bacteria than soil alone. During column testing, it was observed that having a higher surface area facilitates pollutant removal. Whereas most of the biochar displayed removal efficiency in regard to nutrients, indicator bacteria and heavy metals. The effect of drying was not observed from the results but most of the biochar were still able to provide additional benefits. Though over time a slight reduction in the performance could be noticed.

Based on median removal efficiencies, biochar columns can sufficiently remove most of the contaminants. Comparatively, nutrients and indicator bacteria are more significantly removed than heavy metals. WF, BS, NC, and CB biochar column were most the effective while BNM was the least effective for most of the contaminants. BS biochar column did not show any added benefits for phosphate particularly whereas it showed efficient removal capacity for other contaminants. Also, BNS 3% & 6% showed less removal capacity for the nutrients. For the best and worst performance scenarios, the data are analyzed at 90th and 10th percentile while the median result gives the indication for representative performance. Based on the 90th percentile results, all the biochar showed high removal efficiency. Whereas the 10th percentile data shows the leaching problem with every biochar.

Table 5.8 Median percent removal of contaminants from the different biochar column throughout the year. Positive median removal for more than 20% is highlighted in blue whereas negative removal is highlighted in red.

Biochar type	WF	BS	NC	CB	BNM	BNS 6%	BNS 3%
Phosphate (mg/l)	54%	-65%	52%	23%	51%	39%	63%
Ammonia (mg/l)	57%	82%	47%	89%	14%	-1%	14%
Nitrate (mg/l)	37%	74%	53%	75%	45%	43%	14%
Nitrite (mg/l)	63%	80%	93%	84%	37%	11%	47%
Total coliform (/100mL)	76%	62%	70%	93%	1%	64%	81%
***E. coli* (/100mL)**	99%	99%	72%	100%	33%	99%	99%
Fecal coliform (/100mL)	78%	66%	91%	98%	-8%	88%	94%
***Enterococci* (/100mL)**	65%	7%	73%	91%	-308%	67%	83%
Al (mg/l)	6%	38%	39%	35%	-89%	8%	42%
Cu (mg/l)	4%	5%	7%	6%	-3%	71%	-9%
Cr (mg/l)	27%	10%	11%	3%	38%	34%	22%
Zn (mg/l)	68%	46%	48%	52%	33%	26%	48%
Mn (mg/l)	65%	99%	66%	99%	67%	43%	46%
Pb (mg/l)	-3%	51%	-41%	-2%	-34%	-46%	-3%
Mg (mg/l)	2%	26%	-22%	15%	24%	20%	-8%

Table 5.9 The 90th percentile removal of contaminants from the different biochar column throughout the year. Positive removal is highlighted in blue whereas negative removal is highlighted in red.

Biochar type	WF	BS	NC	CB	BNM	BNS 6%	BNS 3%
Phosphate (mg/l)	81%	8%	73%	58%	84%	64%	83%
Ammonia (mg/l)	80%	93%	80%	94%	39%	57%	80%
Nitrate (mg/l)	61%	84%	69%	81%	56%	54%	40%
Nitrite (mg/l)	95%	97%	98%	100%	93%	71%	90%
Total coliform (/100mL)	100%	96%	99%	100%	72%	99%	98%
***E. coli* (/100mL)**	100%	100%	100%	100%	93%	100%	100%
Fecal coliform (/100mL)	95%	91%	96%	100%	93%	99%	98%
***Enterococci* (/100mL)**	85%	73%	99%	99%	80%	96%	98%
Al (mg/l)	65%	126%	115%	95%	39%	78%	208%
Cu (mg/l)	226%	68%	242%	748%	79%	205%	111%
Cr (mg/l)	127%	2509%	268%	87%	763%	138%	207%
Zn (mg/l)	828%	430%	244%	523%	177%	301%	281%
Mn (mg/l)	93%	100%	99%	100%	93%	93%	90%
Pb (mg/l)	82%	121%	69%	129%	54%	89%	83%
Mg (mg/l)	10%	35%	-6%	37%	41%	27%	20%

Table 5.10 *The 10th percentile removal of contaminants from the different biochar column throughout the year. Positive removal is highlighted in blue whereas negative removal is highlighted in red. *Note: Indicator bacteria data are shown at 20th percentile.*

Biochar type	WF	BS	NC	CB	BNM	BNS 6%	BNS 3%
Phosphate (mg/l)	-656%	-316%	-5%	-94%	-39%	-161%	-1122%
Ammonia (mg/l)	-159%	-211%	-30%	-51%	-70%	-83%	-2319%
Nitrate (mg/l)	5%	21%	44%	40%	36%	-12%	-193%
Nitrite (mg/l)	-67%	-167%	1%	4%	-135%	-100%	-49%
Total coliform (/100mL)	-80%	-21665%	-23%	44%	-703%	-60%	-63%
***E. coli* (/100mL)**	-403%	-543%	-202%	87%	-81%	78%	68%
Fecal coliform (/100mL)	56%	-57%	57%	87%	-149%	42%	55%
***Enterococci* (/100mL)**	-22%	-662%	-753%	57%	-963%	-17%	48%
Al (mg/l)	-453%	-312%	-111%	-50%	-935%	-600%	-393%
Cu (mg/l)	-34757%	-11128%	-12270%	-86%	-5966%	-29324%	-23784%
Cr (mg/l)	-1179%	-273%	-2148%	-931%	-94%	-1434%	-200%
Zn (mg/l)	-85%	-1830%	-217%	-3773%	-24%	9%	-506%
Mn (mg/l)	-649%	89%	-70%	85%	-483%	-482%	-770%
Pb (mg/l)	-402%	-287%	-437%	-145%	-247%	-381%	-550%
Mg (mg/l)	-284%	-201%	-1100%	-201%	-204%	-217%	-3420%

5.5 Summary of Findings

The study was conducted to find the removal of efficiencies of nutrients, indicator bacteria, and heavy metals through batch testing and column testing. Preliminary batch testing shows positive results with most of the biochar. Samples with higher biochar content show higher removal efficiency. However, due to higher stormwater to soil biochar mixture, the effect of biochar in the mixture was insignificant because 6% weight of the biochar in the column covers sufficiently higher volume. All the biochar shows higher added removal efficiency for nutrients, indicator bacteria, and heavy metals. The performance of the column over the period decreases a bit but most of the columns were still able to sufficiently add the benefits for contaminant removal.

- All ten biochar were tested with both the soils at two different concentrations (i.e., 3% and 6% by the weight of the soil) to find the efficiency of the biochar for the contaminant's removal. WF, BS, NC, SR, CB, BNM, and BNS showed positive results for nutrients as well as indicator bacteria removal. BNC and TA showed the lowest removal efficiency. For the heavy metals analysis, the top performing biochar were also the same biochar which includes BS, NC, SR, CB, BNM, and BNS.
- During the batch testing, TA biochar showed negative removal efficiency. All the biochar at 6% comparatively showed better performance than 3% for nutrients, indicator bacteria, and heavy metals analysis.
- Six best performing biochar were selected for column study. And the result from column study shows that NC, BNM, and SR biochar columns were the top performers. Whereas, BNM and BNS biochar column showed the lowest removal efficiency. BS, NC, and CB biochar showed higher

removal capacity for indicator bacteria analysis. And the least performing biochar were BNM and BNS.

- Al, Cu, Cr, and Mn heavy metals were easily captured by BS, CB, and NC whereas BNM and BNS showed the lowest added benefits. Less metals uptake with biochar could be attributed to the higher concentration of heavy metals in the biochar (Table 4.7).
- Over the period of nearly a year, the columns exhibited a reduction in contaminant removals. Overall CB, BS, and NC biochar showed comparatively better performance and were least affected by the aging.

6. DEVELOPMENT OF A TRIPLE BOTTOM LINE (TBL) MODEL

6.1 Co-Benefits of Green Infrastructure through TBL

The ability for green infrastructure to retain water in soils and filter out pollutants from runoff are well established benefits for these systems. However, the added social and ecological benefits are not traditionally weighed in the decision to implement green infrastructure and low impact development strategies for stormwater management. Recent focus on holistic watershed management (i.e., One Water Approach) departs from conventional centralized approaches. The approach is grounded in the triple bottom line, that aims to achieve a strong and prosperous economy, high quality of life, and a healthy environment. Assessing the 'benefit function' is an emerging key concept useful for evaluating green stormwater infrastructure that mathematically expresses multiple benefits generated by the practice. Recent work demonstrates the ability for modeling tools to capture and quantify co-benefits (such as improving aesthetics, increasing biodiversity, and mitigating heat island effect) associated with healthy landscapes. Here we evaluate these additional benefits by framing each added benefit through a Triple Bottom Line lens. The concept of the triple bottom line assesses the effectiveness of GI in promoting social, environmental, and financial benefits, known as the 3Ps: people, planet, and profit. For this study, we reviewed various storm water toolkits to evaluate the most relevant co-benefits of biochar-amended GI in North Carolina. Tables 6.1 and 6.2 provide a summary of the tools and benefits that were evaluated and considered for model inclusion.

Table 6.1 Published green infrastructure webtools reviewed. Tools with an asterisk (*) were utilized in the TBL workbook.

Toolkit	Owner	Details
NYC Green Infrastructure Co-Benefits Calculator*	NY Department of Environmental Protection (DEP)	Compares life-cycle costs and benefits of GI in environmental, social and economic contexts.
Green Values Storm water Management Calculator*	Center for Neighborhood Technology (CNT)	Provides valuation methods for estimating GI benefits based on location and design input factors.
i-Tree Eco*	USDA Forest Services	Demonstrates environmental impacts of various forestry and green spaces using field data.
Storm water Management Model (SWMM)	Environmental Protection Agency (EPA)	Used for large-scale planning, analysis, and design related to stormwater runoff, combined and sanitary sewers, and other drainage systems in urban areas.
National Storm water Calculator (SWC)	Environmental Protection Agency (EPA)	Estimates the annual amount of stormwater runoff from a specific location in the United States (including Puerto Rico), based on local soil conditions, land cover, and historic rainfall records.
Green Infrastructure Wizard (GIWiz)	Environmental Protection Agency (EPA)	Provides users with customized reports containing EPA tools and resources.
Watershed Optimization Support Tool (WMOST)	Environmental Protection Agency (EPA)	Generates cost-effective resources to facilitate integrated water

		resources management across wet and dry climate regions across a watershed.
Integrated Decision Support Tool (i-DST)	Environmental Protection Agency (EPA)	Evaluates options for improving stormwater runoff management using green infrastructure, including ancillary benefits such as reducing inputs to existing grey infrastructure, as well as enhancing green livable cities and augmenting scarce water supplies.
Visualizing Ecosystems for Land Management Assessment (VELMA) Model	Environmental Protection Agency (EPA)	Quantifies the effectiveness of natural and engineered green infrastructure management practices for reducing nonpoint sources of nutrients and contaminants in streams, estuaries, and groundwater for practices such as riparian buffers, cover crops, and constructed wetlands.
Community-enabled LCA of Stormwater Infrastructure Costs (CLASIC)	Environmental Protection Agency (EPA)	Uses life-cycle cost framework to support feasibility and planning of storm water infrastructure.
Green Infrastructure Flexible Model (GIFMod)	Environmental Protection Agency (EPA)	Evaluates the performance of urban stormwater and agricultural green infrastructure practices.
Guide to Assessing GI Costs and Benefits for Flood Reduction	National Atmospheric and Oceanic Administration (NOAA)	Assesses the costs and benefits of green infrastructure to reduce flooding on a watershed scale.
Green Infrastructure Opportunities that Arise During Municipal Operations	Environmental Protection Agency (EPA)	Provides cost-effective ways for municipal green infrastructure projects to be modified or incorporated in public spaces.

Table 6.2 Summary of TBL benefits across primary GI webtools

	The Value of Green Infrastructure, CNT (2010)	Triple Bottom Line Cost Benefit Analysis of Green Infrastructure/Low Impact Development (GI/LID) (2018)	Triple Bottom Line Analysis of Philadelphia's CSO Program, Neukrug and Raucher (2009)
Social	Increases recreational opportunity	Provide educational opportunities	Increased recreational opportunities
	Improves Aesthetics	Increase property values	Property value increase (50%)
	Reduced Noise Pollution	Improve aesthetics	Reduction in heat related fatalities
	Community Cohesion	Improve community involvement	Annual willingness to pay (WTP) for water quality and aquatic habitat improvements
	Public Education	Health Island Effect	Local green jobs
	Reduces noise pollution		Reduction in heat stress mortality
	Urban agriculture		Vehicle delay from construction and maintenance (hours)
			Energy savings/usage
Environmental	Improved water quality	Water Quality	Water quality/aquatic habitat enhancement
	Improve air quality	Carbon Reduction	Change in particulate matter (PM2.5) due to trees (µg/m3)
	Reduced Atmospheric CO2	Air Pollution from Energy Use	Reduction Air quality improvements from trees
	Reduced Energy Use	Carbon Emissions from Energy Use Reduction	Change in ozone due to trees (ppb)
	Habitat Improvement	Reduced stormwater runoff	Electricity savings due to cooling effect of trees (kWh)
	Reduced heat island		Natural gas savings due to cooling effect of trees (kBtu)
	Improves Habitat		Sulfur dioxide (SO2) emissions (metric tons)
	Increases groundwater recharge		Nitrogen oxides (NOx) emissions (metric tons)
			Carbon dioxide (CO2) emissions (metric tons)
Economic	Construction costs	Capital Expenditures	Wetlands created or restored (acres)
	Maintenance Costs	Operations and Maintenance	Avoided Health Effects
	Reduced water treatment needs	Avoided CapEx and O&M on Additional Detention	Reduced (increased) damage from SO2 and NOx emissions
	Reduces Grey infrastructure needs	Avoided CapEx and O&M on Additional Piping	Reduced (increased) damage from CO2 emissions
			Disruption costs from construction and maintenance

6.2 Model Overview

This model is designed to evaluate the potential impact of green infrastructure (GI) on societal, economic, and environmental aspects in a specific geographic area. We aimed to create a model with the framework to assess the social, economic, and environmental metrics with options to include biochar implementation to evaluate scenario with each GI type. The model operates in macro-enabled MS Excel to allow the user to input the details and perform calculations with literary inputs utilizing equations. These results from calculations are then displayed on a dashboard categorized by metrics such as social, economic, and environmental. The user inputs include information such as the location (e.g., county, census tract), footprint, the variation of GI, and the user defined unit cost of the GI. The user can either access dropdown menus or input the value to generate estimates. The results of this model are displays both numerical and graphical formats that allow the user to visualize the potential impact of metrics through interactive charts and graphs that update with changes in user inputs such as the footprint, location, and GI variation.

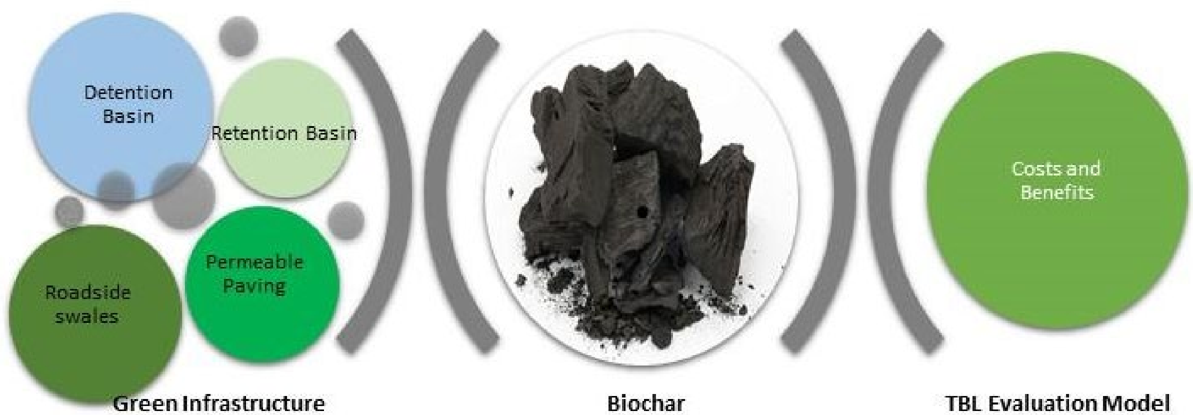

Figure 6.1 Implementation of biochar as soil amendment in green infrastructure

6.3 Economic Module

The economic metrics of green infrastructure include quantifying costs (such as initial costs, annual maintenance costs) and benefits such as improvement in property values, reduced stormwater treatment needs (CNT, 2020; Ch2m Hill, 2011) and savings from biochar-amendment (Mohanty et al., 2018). Additionally, green infrastructure can reduce strain on existing sewer systems, reduce energy intake, reduce flooding and stormwater runoff, and create green spaces (Braden et al., 2010). Economic metrics to quantify costs and benefits of GI and biochar-amended GI are incorporated into an economic module utilizing three metrics, detailed in Table 6.3.

Table 6.3 Metric framing for economic benefits

Economic Benefit	Prior Studies
Green Infrastructure Construction Costs	Center for Neighborhood Technology (CNT) Green Values Calculator (2009)
Green Infrastructure Maintenance Costs	Center for Neighborhood Technology (CNT) Green Values Calculator (2009)
Increase in Property Values	Center for Neighborhood Technology (CNT) - GSI impact on property values (2020) Braden et al. (2010). Zillow National Association of Realtors

Green Infrastructure Construction & Maintenance Costs. Based on the user inputs, the model generates total cost estimates for construction and maintenance for each type of Green Infrastructure (GI). Metrics for costs include construction and maintenance costs which define costs associated with GI installation and maintenance of GI over one year. The estimates can either be user-defined or pre-defined, and the derived literary inputs are specific values to North Carolina. The net present value calculation uses a discount rate of 3.1% over a 30-year life cycle (CNT, 2009). For more information on costs, please refer 'The Green Values® Stormwater Management Calculator Methods'.

Increase in Property Values Economic benefits were quantified with estimated increase in property values, which indicates the potential influence of green infrastructure (GI) to increase neighboring property values. Based on the user-defined location, the model estimated the likelihood for rising property values. The minimum and maximum increase in property value rates for each GI type were determined based on Green Stormwater Infrastructure Impact on Property Values by CNT (see Table 6.4). The property values data include median property values from Zillow and the National Association of Realtors. We multiplied the median property value with the growth rate (CNT, 2020) to determine the minimum and maximum increase value of a property based on a chosen GI.

Equation 10

$$PV = MPV\ (\$) \times\ Gain\ (\%)$$

PV = Increase in Property Value
MPV = Median Property Value at selected location
Gain = Percentage increase in property sale price for GI selection

Table 6.4 Rate of increase in property values according to green infrastructure type

Green Infrastructure Type	Min Property Increase Rate (%)	Max Property Increase Rate (%)
Detention Basins	0.23	-
Roadside Swales	0.38	0.69
Retention Basins	0.23	-
Roadside Vegetation (Grass)	0.38	0.69

6.4 Environmental Module

This module of the workbook focuses on the added environmental benefits of proposed green infrastructure (GI) and biochar-amended GI in North Carolina. The impacts of green infrastructure in the environment are related to the characteristics and prevalence of vegetation and soil. The benefits explored in this module include carbon sequestration, urban heat island mitigation, air and water quality, and storm water control, which align with NY Co-Benefits tool (detailed in Table 6.5). Data were aggregated by county and census tract levels to facilitate the analysis. To demonstrate urban green space, land cover data for forests, parks and other types of vegetation were incorporated into the NC shapefile for grouping.

Table 6.5 Metric framing for environmental benefits

Environmental Benefit	Prior Studies and Published Datasets
Ecosystem Benefits	Hazen and Sawyer (2015) Goulson, Lye, & Darvill (2008) Tallamy & Shropshire (2009) Gamfeldt et al. (2013)
Carbon Sequestration	Creamer et al (2011) Hirabayashi (2014) Wang et al (2022) Hazen & Sawyer Green Infrastructure Co-Benefits Study and Calculator (2015) i-Tree Eco by USDA Forest Services National Land Cover Database (NLCD) National Climatic Data Center (NCDC) National Oceanic and Atmospheric Administration (NOAA) Center for Neighborhood Technology (CNT) Green Values Calculator
Improved Air Quality	Hirabayashi (2014) Gopalakrishnan et al (2018) Hazen & Sawyer Green Infrastructure Co-Benefits Study and Calculator (2015) EPA Air Quality System (AQS) National Oceanic and Atmospheric Administration (NOAA)
Improved Water Quality	International Stormwater BMP Database (AASHTO, 2020) Liu et al. (2015) Battiata et al. (2010)
Reduced Stormwater Mitigation	Liu et al. (2015) Battiata et al. (2010) National Oceanic and Atmospheric Administration (NOAA)

Carbon Sequestration. Carbon sequestration refers to the long-term storage of carbon dioxide and other forms of carbon in soils or vegetation to mitigate the effects of greenhouse gas emissions on global warming (Blaser et al., 2014). Based on the user inputs of the GI type and its location, the calculator will provide results on the amount of carbon sequestered by the selected GI. Pre-defined estimates are derived from literary values associated with annual carbon sequestration rates for shrub, grass, and trees and incorporated into the TBL calculator. The tree and grass values are obtained from the NY calculation and tree data from i-Tree data compiled by Hirabayashi (2014) for the conterminous US in rural, urban, and county areas. These i-Tree values are derived from various data sources such as the National Land Cover Database (NLCD), National Climatic Data Center (NCDC), National Oceanic and Atmospheric Administration (NOAA), and the EPA Air Quality System (AQS). Annual carbon sequestration rates from aboveground were obtained from studies by Wang et al. (2022) for grass and Creamer et al. (2011) for shrubs. The user interface requires the total square footage of the specified GI in order to calculate the annual amount of carbon sequestered for analysis and decision making. Carbon sequestration was calculated based on Equation 11 (detailed below).

$$C_{seq} = GI_{footprint} * (R_{trees} + R_{grass} + R_{shrubs})$$

Equation 11

Where C_{seq} is the total amount of carbon sequestered annually, $GI_{footprint}$ is the total square footage of the selected GI type, R_{trees}, R_{grass} and R_{shrubs} are the annual carbon sequestration rate for trees, grass and shrubs. The sum of each medium's carbon sequestration rate is converted from $g/m^2/yr$ to lbs/sf/yr to meet US measurement metrics. The rates are then multiplied by the GI footprint (in square feet) to estimate the total annual amount of carbon sequestered by the selected GI.

Improved Air Quality. Air quality depends heavily on the ability of trees and other vegetation to employ dry deposition in the removal of common air pollutants such as ozone (O^3), particulate matter (PM_{10} and $PM_{2.5}$) in the atmosphere. Using tree data from i-Tree Database compiled by Hirabayashi (2014) for the conterminous US in rural, urban, and county areas, the annual deposition rates for the aforementioned pollutants are estimated and converted into lbs/sf/yr to meet US measurement metrics. Equation 12 was used to estimate the amount of ozone and particulate matter deposited to the vegetation.

$$D_{air} = GI_{footprint} * P_{average}$$

Equation 12

Where D_{air} is the total amount of air pollutant uptake in pounds, $GI_{footprint}$ is the total square footage of the selected GI type, and $P_{average}$ is the average annual uptake for particulate matter ($PM_{2.5}$, PM_{10}, ozone). The user interface requires the total square footage of the specified GI to calculate the annual amount of pollutant removed by trees in the conterminous US. Multiplying the user input on the GI footage and the average annual pollutant uptake provides the estimated total amount for analysis.

Improved Water Quality. Water quality is based on the concentrations of both influent and effluent flow from the adjacent impervious surfaces for each GI type in nutrient removal. Performance data for the influent and effluent concentrations for various urban storm water BMPs were obtained from the State DOT portal to the International Storm water BMP database (AASHTO, 2020). Median concentrations for both DOT and non-DOT sites were selected as representative values for calculation in the TBL calculator due to limited sample size for the study. Based on the concentrations, the percentage of removal were calculated for comparison with literary values (Liu et al., 2015; Battiata et al, 2010). Concentrations were converted from mg/L to lbs per gallon to facilitate calculations from user input. Equation 13 details the calculation for dissolved pollutant removals.

$$D_{water} = GI_{footprint} * P_{average}$$

Equation 13

Where D_{water} is the total amount of dissolved pollutant uptake in pounds, $GI_{footprint}$ is the total square footage of the selected GI type, and $P_{average}$ is the average annual uptake for organic and inorganic nutrients (nitrogen, phosphorus, ammonia and nitrates/nitrites). Here, the estimated total amount of dissolved nutrients that are removed from biochar-amended GI is provided from the volume of storm water retained by the selected GI.

Reduced Stormwater Mitigation. Stormwater volume retention is estimated to demonstrate the mitigation performance for the selected GI. Literary values are obtained from Battiata et al. (2010) and Liu et al. (2015). These values are derived from simulations in urban watersheds at various scales. Based on user input, default values for volume reduction are incorporated into the calculation. Regional annual rainfall values are obtained from the NOAA to buttress the annual volume of stormwater retention. Equation 14 was utilized to quantify the volume of stormwater mitigated.

$$\mathrm{Q_{total}} = \left[\mathrm{P_{annual}} * \mathrm{GI_{footprint}} * \mathrm{V_{retained}}\right] * 144\,\frac{\text{square inch}}{\text{SF}} * 0.00433 \text{ gal per cubic inch}$$

Equation 14

Where Q_{total} is the total annual volume of storm water retained by the selected GI in gallons, P_{annual} is the reported annual precipitation of the selected GI location in inches, $V_{retained}$ is the percentage of rainfall volume retained by the selected GI type. Conversion factors are incorporated to convert the volume from inches per year to gallons per year. Using literature from the runoff reduction method, the runoff reduction and pollutant removal rates of the selected GI was compiled in Table 6.6 for incorporation into the TBL calculator (Battiata et al., 2010; Liu et al., 2015). Using the available data and equations for each co-benefit, a detailed dashboard was created using a macro-enabled Excel file. In the Excel dashboard, charts and graphs were created from dummy user input values that showed the results for environmental, social, and economic benefits.

Table 6.6 Summary of GI type performances with rainfall retention and pollutant removal (Battiata et al., 2010; Liu et al., 2015Mohanty et al., 2018; AASHTO, 2020)

GI Type	Runoff Reduction (%)	Total Phosphorus Removal (%)	Total Nitrogen Removal (%)
Roadside swale	42	-40	11
Bioretention ponds (wet pond)	7	51	26
Detention Basins	33	26	4
Roadside vegetation (grass)	34	-30	10
Biochar-amended Bioretention systems	45 to 67	30 to 40	60

Ecosystem Benefits. Ecosystem benefits assess the potential co-benefits from GI installation in terms of pollinator support, native habitat support, and biodiversity support by aggregating responses across the three categories. To evaluate these metrics, we followed the New York Co-Benefits tool where it provides a framework for assessing the potential to improve ecosystem benefits to quantify the benefits in terms of ecological and socio-economic indicators. User needs to input on flowering vegetation, native vegetation, and number of plant species. Metrics including the quantity of flowering vegetation, native vegetation, and plant species richness are used to quantify improvement in each area as ‘low,’ ‘medium,’ and ‘high.’

Pollinator Support. This metric measures the ability of a particular area or ecosystem to support pollinator populations, based on the presence and abundance of flowering vegetation. It considers the quantity and quality of floral resources that are available to pollinators, as well as their distribution and accessibility. Pollinator support can be evaluated using various indicators such as the number and diversity of pollinators, their foraging behaviour, and reproductive success. The inputs used to calculate this metric are the quantity and quality of flowering vegetation in the area, which can be determined through visual surveys or remote sensing data (Goulson, Lye, & Darvill, 2008).

Native Habitat Support. This metric assesses the degree to which an area or ecosystem provides suitable habitat for native species, based on the presence and abundance of native vegetation. It considers factors such as habitat quality, connectivity, and fragmentation, as well as the degree of disturbance and land use changes. Native habitat support can be evaluated using various indicators such as the number and diversity of native species, their population trends, and their distribution patterns. The input used to calculate this metric is the quantity and quality of native vegetation in the area, which can be determined through visual surveys or remote sensing data (Tallamy & Shropshire, 2009).

Biodiversity Support. This metric measures the level of biodiversity in a particular area or ecosystem, based on the number of plant species present. It considers both the richness and evenness of plant species, as well as their distribution patterns and functional diversity. Biodiversity support can be evaluated using various indicators such as the number and diversity of species, their genetic variability, and their ecosystem services. The input used to calculate this metric is the number of plant species in the area, which can be determined through visual surveys or field sampling (Gamfeldt et al., 2013).

6.5 Social Module

This focuses on the community’s emerging issues and benefits from investing in Green Infrastructure with long-term and high return benefits. Green infrastructure encourages a greater public awareness and appreciation of resource management while strengthening social cohesion, especially considering existing barriers (Lafortezza et al., 2013). Marginalized communities experience vulnerabilities due to improper environmental burden distribution. These can be addressed by GI implementation to address health equity (improving asthma potential), cultural ecosystem services (access to recreational space and aesthetic value) (Govers 2016; Boone et al., 2009) and community-based needs (Potentially Underserved Communities, Educational advancement) to relieve the predisposed burdens (Clark & Miles, 2021; Kabisch & Haase, 2014). By potentially increasing the value of the property market and reducing the prevalence of asthma, GI installation additionally has the potential to empower marginalized communities and individuals. Because of the awareness generated by GI, subsequent generations will also be able to recognize these benefits (Tayouga, 2016). A range of metrics have been adopted to evaluate the potential benefit to society based on community needs (Table 6.7). Therefore, outcomes of this module will vary geographically and not by GI type.

Table 6.7 Metric framing for social benefits

Social Benefit	Prior Studies and Published Datasets
Willingness To Pay (Social Acceptance)	Wong and Montalto (2020) American Community Survey (ACS) (2010) Zalejska-Jonsson et al. (2020)
Aesthetic Potential	Center for Neighborhood Technology (CNT) - GSI impact on property values (2020) Zillow National Association of Realtors
Asthma Incidence Reduction Potential	Behavioral Risk Factor Surveillance System Survey (BRFSS) (2019) Centers for Disease Control and Prevention (CDC)
Education Improvement Potential	American Community Survey (ACS) (2010) Tayouga (2016)
Potential to Improve NCDEQ Potentially Underserved Communities	American Community Survey (ACS) (2010) Adebowale and Schwarte (2007)
Potential to Improve Lack of Green Space	National Land Cover Dataset (NLCD) Govers (2016) Boone et al (2009)

Willingness to Pay (WTP). WTP, which derives from resident preferences and exposure to various green infrastructure, is the proportion of a population that values green infrastructure installation. According to Wong & Montalto (2020), willingness to pay for green infrastructure is based on a combination of two important factors: the location's population (Pop) and the Public Value Coefficient (PVC). A higher value indicates the proportion of people who appreciate nearby GI locations and are willing to pay for GI installations which indicates a greater potential for the success of GI projects.

$$\text{Willingness To Pay (WTP)} = \frac{(\text{Pop}_1 * \text{PVC}_1) + (\text{Pop}_2 * \text{PVC}_2) + \cdots (\text{Pop}_\text{n} * \text{PVC}_\text{n})}{\text{n}}$$

Equation 15

$$\text{Willingness To Pay (WTP)} = (\text{Pop}_1 * \text{PVC}_1)$$

Equation 16

WTP = Willingness to Pay
Pop_1 = Population in the selected location
PVC_1 = Public Value Coefficient

Based on the research of Wong and Montalto (2020), we categorize several forms of green infrastructure (GI) and assume public value coefficients (PVCs) for each category. We specifically categorized Detention Basins, Roadside Swales, and Retention Basins as Bio Swales. Furthermore, we included Roadside Vegetation (Grass) under the category of Public Parks. Based on the total PVCs mentioned in Table 6.8 and the research by Wong and Montalto, we then made assumptions about the PVC values for each kind. The demographic data county wise in NC were obtained from the American Community Survey (ACS), 2010 data with a five-year interval.

Table 6.8 Aggregate Public Value Coefficients for Green Infrastructure

Green Infrastructure Type	Aggregate Public Value Coefficient
Detention Basins	0.52
Roadside Swales	0.52
Retention Basins	0.52
Roadside Vegetation (Grass)	0.57

Aesthetic Value. The Center for Neighborhood Technology (CNT) asserts that using green infrastructure can improve a community's aesthetic appeal. This metric compares the median property value of a county with the median property value of the entire state while considering the lowest and maximum growth in property value factor. To evaluate this metric, we first obtained data on median property values for each county in the NC state from Zillow and the National Association of Realtors. If the county's median property value was below the state-wide median property value, the metric indicated a potential to improve with a "YES" result. If the county's median property value was above the state-wide median property value, the metric indicated no potential to improve with a "NO" result.

Asthma. Asthma is a leading health consequence linked to environmental causes, according to the CDC. The implementation of Green Infrastructure (GI), however, can aid in minimizing the effects of these elements and advancing public health. This metric shows the likelihood of lowering the incidence of asthma in the local population. The model uses the proportion of self-reported asthma cases from the BRFSS survey as the potential to improve asthma by showing case percentage of cases in the county. This data is reported at the region level which has been broken down to county levels.

Education. This metric evaluates the potential for strengthening the future generation by considering the proportion of the population under the age of 18. The population percentage that is most likely to benefit is used as a metric to analyse the location's ability to improve educational outcomes. Greater potential for the positive effects of education is indicated by a higher percentage of people under the age of 18. The demographic data were acquired from the 2010 American Community Survey (ACS) five-year interval county level and census tract level dataset. For information on zip code conversion to census tract table.

Potentially Underserved Communities (NCDEQ Definition). This metric assesses the equitable treatment regardless of background. The measure combines two important demographic indicators, such as the non-white population and poverty, to evaluate the likelihood of environmental justice. The model uses the percentage of the population who are non-white and below the poverty line in the selected county to assess the potential for fair and equitable treatment with regards to environmental benefits and liabilities. A higher percentage of the population who are non-white and below the poverty line indicates a greater potential for environmental justice concerns. The demographic data were acquired from the 2010 American Community Survey (ACS) five-year interval county level and census tract level dataset.

Potential to Improve Green Spaces. This metric evaluates the percentage of vegetation cover and urban green space in a selected county, as compared to the median value for the region. The proportion of vegetation cover in metropolitan areas, excluding impervious surfaces, is calculated using the National Landcover Dataset (NLCD), and it serves as an indicator of the potential for expanded development of green space. To apply this metric, the specified county's NLCD data were retrieved, and counties within the NC state are located. Calculated and compared to the region's median value is the percentage of vegetation cover in these areas that is not impermeable. If the county's percentage of urban green space is lower than the median number, this shows rating “YES” indicating the potential to improve green areas in selected location.

7. CONCLUSIONS AND RECOMMENDATIONS

Biochar-amended soils displayed improved stormwater capturing capabilities and increased removal of nutrients, metals, and indicator bacteria. However, the performance across the samples varied in a manner that did not identify one biochar that performed the best across all the metrics tested. Instead, variations that were noted in the physicochemical properties of the individual biochar carried over into differences in the performance type. Certain biochar lends themselves to being chosen to optimize stormwater capturing and others to be chosen when optimizing contaminant removals. Therefore, we've presented the outcomes of this work in a manner that supports the selection of an appropriate biochar based on the benefit that is most important. To facilitate this, outcomes of the biochar laboratory analysis were aggregated into a webtool and juxtaposed with ordering and purchasing information for future application. In addition to the capture and treatment of stormwater, we have identified several approaches to quantifying the added benefits of green infrastructure systems and have aggregated the findings into a webtool designed for use across North Carolina.

Specific conclusions and recommendations of this study are as follows:

- A biochar vendor study was conducted and summarized into a NC Biochar Locating Tool to facilitate the future implementation of biochar amendments.
    - Locally sourced biochar supplies are limited, but several sources are available at the national scale.
    - Several suppliers offer biochar supplies in volumes suitable for large-scale applications, and long-term storage of biochar is warranted due to the long half-life of the materials.
    - Outcomes of the biochar laboratory analysis were aggregated into a webtool and juxtaposed with ordering and purchasing information for future application.
- Physicochemical properties of biochar varied across the samples, but overall displayed the potential to improve hydraulic properties of amended soils.
    - Results from the pycnometer tests show a wide range for specific gravities. Where some of the biochar are light as 0.86 g/cm^3, other biochar are as high as 1.54 g/cm^3.
    - The effect of density as well as effect of biochar application rates were also found in dry bulk density. As the biochar amount increases from 3% to 6% the dry bulk density decreases with all the biochar.
    - Methylene blue adsorption capacity of biochar shows a difference in adsorption capacity of various biochar which suggests variations across biochar surface areas. WF, BS, SR, and CB were top performers; BNM and BNM showed the lowest adsorption capacity.
    - Heavy metals analysis yielded levels of aluminum, magnesium, and manganese in biochar samples and soil-only samples. Aluminum is the only metal at consistently higher concentrations in biochar than soil.
    - Due to improved porosity, most of the biochar showed higher saturated hydraulic conductivity. SR, CB, BNM, and BNS mixture sample showed comparatively higher infiltration capacity with both soils. BS, CB, SR, and BNM showed the higher water retention capacity whereas TA was the lowest performer with both soils.
    - Overall, higher percentages of the biochar comparatively show the better performance and this study found that 6% biochar content by the weight of the soil showed higher efficiencies.
- Nutrient, metal, and indicator bacteria removals of biochar-amended soils were performed by batch testing and column testing.
    - Batch testing shows positive result with most of the biochar. And samples with higher biochar content show higher removal efficiency.

    - All biochar mixtures displayed higher removal efficiency for nutrients, indicator bacteria and heavy metals.
    - Column study results show that WF, NC, BNM, and CB biochar columns were the top performers for nutrient removal. Whereas, BS and BNS showed the lowest removal efficiency. Especially, BS biochar column showed the lowest phosphate removal.
    - For the indicator bacteria analysis, columns with BS, NC, and CB biochar showed higher removal capacity whereas the least performing biochar were BNM and BNS.
    - Al, Cu, Cr, and Mn heavy metals were easily captured by BS, CB, and NC biochar whereas BNM and BNS biochar showed the lowest added benefits. Less metals uptake with biochar could be attributed to the higher concentration of heavy metals in the biochar.
    - After nearly one year of testing, the columns exhibited a reduction in contaminant removals. Overall, the columns with CB, BS, and NC biochar showed comparatively better performance and were least affected by aging.
- Social, environmental, and economic factors associated with green infrastructure systems have been aggregated into a triple bottom line workbook.
    - Social benefits noted in prior studies were incorporated into the workbook and demonstrate the ability for green infrastructure to improve community dynamics.
    - Several social and environmental benefits intersect with environmental health, such as improved air quality and being instilled in an area with increased asthma incidence, which highlights the potential role of GI in improving community health.
    - Laboratory results for nutrient removals were integrated into the environmental benefits for biochar-amended green infrastructure selections to support future cost-benefit analyses.
    - Several studies note the potential ability for green infrastructure to be used to help address social vulnerability and overburdened communities. To assist with any future planning of these efforts, the TBL workbook identifies whether a proposed location is considered as potential underserved community (as defined by NCDEQ), based on user-defined census tracts.

8. IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

Over the course of the project information was communicated to NCDOT personnel in the Environment and Hydraulics Divisions by means of progress reports and presentations. This final report summarizes the project's findings in a manner that facilitates their implementation by NCDOT. Portions of the results will also be disseminated in a future doctoral dissertation and master's thesis of students working on the project (Mohammad Khalid and Neetu Donkada respectively). Further, results will be disseminated in peer-reviewed journal articles to share the outcomes with the broader scientific community. In addition to the written documentation of study outcomes, technology in the form of a biochar locator webtool and TBL benefits workbook are being provided to NCDOT. Utilizing this information and technology delivered through this project, NCDOT will be able to implement field tests with the biochar selected in this project, select biochar based on site performance requirements (stormwater capture vs. treatment), apply knowledge gained from biochar performance and added benefits to update the current NCDOT Stormwater Best Management Practices.

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10.A. APPENDIX A: LITERATURE REVIEW

1.0 Introduction

Roadside stormwater control measures (SCMs) can improve water quality, decrease pollutant infiltration, and decrease runoff. Often categorized as low impact development (LID) and green infrastructure (GI), SCMs such as sand filters, filter strips, bioswales, infiltration trenches, and bioretention systems can incorporate biochar to achieve and improve outcomes (Mohanty et al. 2018; Boehm et al. 2020). Biochar amendments in these systems, including direct mixing with roadside soils, can be long lasting, cost-effective, and improve the removal of harmful pollutants (Dai et al. 2019, Boehm et al. 2020, Kuoppämaki et al. 2021) while mitigating runoff (Imhoff and Nakhli 2017), compaction (Ghavanloughajar et al. 2020, Yoo et al. 2020), and erosion (Jien and Wang 2013).

Biochar is a "fine-grained charcoal made by pyrolysis, the process of heating biomass (e.g., wood, manure, crop residues, solid waste) with limited to no oxygen in a specially designed furnace capturing all emissions, gases, and oils for reuse as energy" (USBI 2020). Commonly leveraged for its carbonaceous and porous properties, biochar can be used in a variety of settings such as agriculture, biofuel, wastewater, and carbon retention (Sohi et al. 2010, Lehmann and Joseph 2015, International Biochar Initiative 2018; Wang and Wang 2019). Due to its properties, biochar can improve soil and water quality through nitrate removal (Berger et al. 2019, Imhoff et al. 2019a), filtration of metals (Kuoppämaki et al. 2021), retention of water and trace organic compounds (ToRCs) (Ulrich et al. 2017, Dai et al. 2019), bacterial contaminant removal (Berger et al. 2019), improved soil microbial communities (Jien and Wang 2013, Yoo et al. 2020), increased hydraulic conductivity (Omondi et al. 2016, Imhoff and Nakhli 2017), increased aggregate stability (Omondi et al. 2016; Somerville et al. 2020), and increased cation exchange capacity (CEC) (Jien and Wang 2013, Li et al. 2019).

Biochar is more cost effective than activated carbon (Ulrich et al. 2017; Mohanty et al. 2018) and can have a long-life span amidst uncertain rainfall conditions (Ulrich et al. 2017, Imhoff et al. 2019a, Berger et al. 2019). However, there is substantial variability in biochar performance based on feedstock, pyrolysis temperature, soil properties, and biofilter design. For example, hydraulic conductivity generally decreases with biochar applications in sand media (Boehm et al. 2017, Ghavanloughajar et al. 2020, Le et al. 2020), but increases in other circumstances, including with compost mixtures (Kuoppämaki et al. 2021), clay soils (Boehm et al. 2017), and in tilled roadside silt loam soils (Imhoff and Nakhli 2017). Therefore, it is of prime importance to choose biochar type based on the desired outcome and account for the soil composition and biofilter design due to observed variability across performance measures (Omondi et al. 2016, Mohanty et al. 2018, Boehm et al. 2020, Minnesota Pollution Control Agency, 2021). Overall, biochar amendments have the potential to exhibit cost-effective, long lasting, and diverse applications under uncertain rainfall conditions and improve roadside stormwater management (Ulrich et al. 2017, Berger et al. 2019, Boehm et al. 2020).

1.1 Biochar Overview

Feedstock type, pyrolysis temperature, and soil composition all influence the effects of biochar in relation to contaminant removal, hydraulic conductivity, porosity, and other metrics for soil and water quality (Omondi et al. 2016, Li et al. 2019, Hassan et al. 2020). The biochar itself has unique biological, physical, and chemical properties that influence these performance measures (Mohanty et al. 2018, Liu et al. 2017).

For example, high temperature pyrolyzed biochars tend to have a high specific surface area (SSA) and microporosity (Boehm et al. 2017, Mohanty 2018) and are generally expected to have higher TOrC and contaminant removal capacities (Qian et al. 2014, Ulrich et al. 2015, Boehm et al. 2017).

Although biochar can be produced from a wide range of organic materials, the most common feedstock types used in stormwater related studies include softwoods, hardwoods, and hay produced at temperatures from 250-1000^{o}C. In our review, most studies used wood-derived biochars, such as pine or birch, produced at a range of pyrolysis and gasification temperatures from 380-1000C. Many studies also used localized feedstocks such as white lead trees (Jien et al. 2013) or rice husks (Kim et al. 2021), indicating further sustainable opportunities for biochar supply and use. For studies conducted in the United States, many used commercially available biochar from companies such as Biochar Now, Black Owl Biochar, or Mountain Crest Gardens.

In the context of roadside soil amendment applications, there are some important physical and chemical characteristics for biochar. Physical properties include particle size distribution, bulk density, porosity, and surface area. These properties are important to characterize in stormwater biochar studies because the outcomes are different based on biochar type and soil composition, therefore carrying important implications for appropriate context and use of biochar as a roadside soil amendment. For example, many studies have noted that bulk density decreases with biochar mixtures (Herath et al. 2013, Jien and Wang 2013, Omondi et al. 2016, and Agenagenu et al. 2017). Increased porosity has also been noted as a positive influence for increasing stormwater flow. Chemical properties include pH, hydraulic conductivity, and nutrient content.

For example, it is generally seen that hydraulic conductivity decreases when biochar is used with sand media but increases when used in clay soils (Boehm et al. 2020). Additionally, many studies noted that water quality improvements are possible with biochar application, namely for nitrates (Bock et al. 2015, Imhoff et al. 2019a), TOrCs (Ulrich et al. 2015, Ulrich et al. 2017) or metals (Kargar et al. 2015, Kuoppamäki et al. 2021). There are many additional physical and chemical properties covered in these stormwater studies.It appears that there is no universal or one-size-fits-all combination of soil type with biochar type to achieve consistent outcomes (Mohanty et al. 2018; Minnesota Stormwater Manual 2021).

One reason why there are varied results is because there are also a great variety of biofilter and GI designs. The majority of studies reviewed were conducted in laboratory conditions using simulated stormwater and tested a suite of outcomes. Additionally, many studies were conducted using fixed laboratory conditions or studied a new biofilter design. It is common that roadside areas modified for stormwater management will often contain mixed media, including sand, compost, or vegetation, rather than solely applying biochar as an amendment for tilled roadside soils. These mixtures also influence characteristics such as denitrifying microbial communities, attachment of metals/TOrCs, infiltration, hydraulic conductivity, soil stability, CEC, porosity, water retention, bulk density, and more. For example, many of the studies reviewed incorporated additional media such as compost (Kargar et al. 2015, Ghavanloughajar et al. 2020), woodchips (Berger et al. 2019) and sand (Bolster 2019, Le et al. 2020) as comparisons to biochar amendments or combinations. Others tested novel biofilter designs (Bock et al. 2015, Boehm et al. 2020, Kuoppämaki et al 2021). However, even with this variability, the continued proliferation of biochar stormwater studies is promising. Results from field and compaction studies, discussed in more detail in later sections, also highlight the potential widespread viability of biochar for roadside amendment purposes.

1.2 Literature Analysis Overview

Our literature analysis included multiple related review papers and individual scientific studies to assess the current state of the science in biochar-stormwater-soil amendment research. Across the papers, there was variance in soil and stormwater composition, effects studied (e.g., compaction, metal removal, vegetation growth, drought effects), and subsequent results. Few concrete trends were present across the ~50 papers reviewed, reflecting the complexity of factors influencing biochar soil amendment targets, design, and performance. However, several trends can be seen: (i) Biochar generally decreases bulk density and increases porosity when mixed with soils or compost (Omondi et al. 2016, Kim et al. 2021), (ii) Saturated hydraulic conductivity tends to increase in clay soils and decrease in sandy soils (Jeffery et al. 2015, Boehm et al. 2020), (iii) Nitrates and ToRCs have been decreased in multiple soil compositions and biofilter designs (Bock et al. 2015, Berger et al. 2019, Imhoff et al. 2019a), and (iv) There is a clear need for additional field scale studies.

Additionally, very few studies were long term (Jien and Wang 2013, Herath et al. 2013, Imhoff et al. 2019a, Somerville et al. 2020). However, those that were conducted over a longer period, even under simulated conditions, were promising for the longevity of biochar in relation to compaction and erosion resilience, increased porosity, and flood mitigation (Kuoppamäki et al. 2021, Ashoori et al. 2019). Therefore, there is not only a need for field-scale, site-specific studies of biochar, but longer-term studies to understand biochar amended soil's resilience and longevity.

In the following sections, we address multiple applications and benefits of biochar, highlighting physical and chemical properties of biochar-amended soils that influence performance for stormwater-related metrics such as hydraulic conductivity, metal and contaminant removal for water quality improvements, and other physical properties such as erosion reduction and compaction resistance. We also highlight results of existing field studies and echo current state-of the science to advocate for additional field studies and improved soil-biochar classification. We also discuss trends, disparities, and missing knowledge in the observed effects of biochar and soil composition on physical and chemical properties relevant to SCMs such as soil performance (porosity and bulk density), water quality improvement (nutrient, bacteria, and metal removal), and water capture (pH and Ksat). Ultimately, our study project will leverage this literature analysis to design laboratory experiments that will contribute to the existing state of the science by demonstrating biochar outcomes with soils native to North Carolina as well as provide groundwork for field-scale roadside amendment experiments.

2.0 Applications and Potential Benefits

2.1 Biochar and Influence of Soil Physical and Chemical Properties

Porosity is an important indicator for soil stability, water drainage, and soil quality for vegetation root growth (Jeffery et al. 2015, Mohanty et al. 2018, Kim et al. 2021). Specifically, macroporosity also influences saturated hydraulic conductivity (Herath et al. 2013) and therefore is a relevant metric to study for biochar soil amendment in stormwater applications (Imhoff and Nakhli 2017). Amendment affects the interpore relationship between soil and biochar and therefore can alter soil porosity and bulk density (He et al. 2021). Generally, a low bulk density is correlated with a high porosity and implies better water holding efficiency and a decrease in erosion possibility (He et al. 2021).

Improved porosity can also be related to improved aggregation and potentially soil drainage and saturated hydraulic conductivity. Due to biochar's porous internal structures, it is expected that biochar amendment would increase porosity, and this is consistent with what is seen in many studies. For example, Omondi et al.'s (2016) meta-review saw an 8.4% increase in porosity, with the greatest increase in coarse textured soils using medium temperature biochars as compared to high temperature biochars. Herath et al. (2013) observed increased porosity in Alfisol and Andisol biochar amended soils with subsequent effects such as increased hydraulic conductivity. Sandy clay loam and clay soils have also seen porosity improvement with biochar addition (Jien and Wang 2013, Omondi et al. 2016). Additionally, Le et al. (2020) saw decreased porosity with fine particles of biochar during a compaction study, thus fine particulates either in the soil or biochar should be removed if possible and coarser sands and biochars should be used to improve porosity and ideally also hydraulic conductivity.

Bulk density is another related physical property that many studies reported demonstrated improvement through biochar amendment. Generally, it would be expected that low bulk density and high porosity assist in water holding. However, He et al. (2021) argue that in biochar amended soils, a low bulk density may not have the same effect on water retention, and that other factors such as particle size distribution, pore volume, and hydrophobicity also play a role. Despite this series of additional factors, many papers discussed lower bulk density in biochar amended soils. For example, in Omondi et al.'s (2016) review paper, they saw that bulk density reduced on average of 7.6% with biochars produced at medium temperatures (250-500C). Additionally, they saw that bulk density was negatively correlated to porosity and available water holding capacity and that the effect was greater on coarse soils than fine soils. In sandy clay loam soils, biochar improved bulk density. Bolster et al. (2019) also saw a decrease in bulk density for small sand media with no change for medium and large sand, using softwood pine medium temperature (550C) biochar from Biochar Now using multiple application rates. Somerville et al. (2019) found that after 6 months, soil with municipal green waste compost with biochar had a smaller bulk density than biochar alone and that after two years, the effects on bulk density were maintained. Jien and Wang (2013), Herath et al. (2013), Agenagenu et al. (2017), and Kim et al. (2021) all reported decreases to bulk density with biochar amendment. Hussain et al. (2020) present decreased bulk density in 13 of 21 papers reviewed, across sand types (loam, clay, sandy loam, sand, silty loam) and biochar feedstock types (hay, peanut shells, dairy manure, acacia tree, hardwood woodchips) at mostly mid-temperature pyrolysis (350-600C).

Particle size and distribution influences multiple other factors, such as hydraulic conductivity. For the case of contaminant removal for both bacteria and heavy metals, smaller biochar sizes could improve outcomes (Boehm et al. 2020). However, small biochar and sand sizes can also lead to clogging and poor drainage. For example, in Liu et al.'s (2017) comprehensive analysis of biochar particle size, they found that subsequent hydrological metrics such as wilting point, plant available water content and field capacity all increased with biochar particle size. Subsequently, Ghavanloughajar et al. (2020) found that particle size distribution shifted under both dry and wet compaction conditions and that biochar released fewer particles than compost. Nakhli et al. (2021) also highlighted the possibility of spatial heterogeneity especially under low moisture conditions when packing and mixing biochar amendments, therefore they suggest packing under moist conditions to allow for better mixing and distribution.

Under real life and field conditions, particle size distribution and porosity may change based on rainfall, vegetation, settling, compaction, biological activity, and other factors. Therefore, it is important to discuss the evolution of biochar-soil relationships under changing and longer-term conditions. For example, it is generally agreed that biochar increases aggregate stability and macroaggregate formation in soils (Omondi et al. 2016, Somerville et al. 2020, Yoo et al. 2020). These properties may also enhance macroporosity and each of these characteristics are generally associated with a decrease in erosion and runoff and are therefore of interest for SCMs. Imhoff et al.'s (2019b) stormwater infiltration study highlighted the formation of water-stable macroaggregates with 4% wood biochar application to roadside sandy loam soils noting that aggregates formed and broke apart seasonally, but at all depths and seasons measured, their biochar field cores had more macroaggregate formation than the control. Their study concluded that biochar could stabilize soil aggregates under wet conditions, that biological activity aids aggregate formation, and aggregates over 2mm need more than 16 weeks to form.

Yoo et al. (2020) also demonstrated improved soil aggregate formation in stressed urban roadside soils (simulated in the lab) and speculated that the porous nature of biochar itself helps provide habitats for microbes that assisted in vegetation growth for the amended soils. This hypothesis regarding aggregate formation benefits and microbe habitat provisioning by biochar pores is echoed elsewhere (Somerville et al. 2020). Somerville et al. (2020) suggest that there is a "synergistic" interaction between the biochar and compost in a clay field site for water stable macroaggregates. Additionally, Kim et al. (2021) also saw an increase in macroaggregates over 60 days in their study on the effects of drought on vegetation in urban soils. Therefore, this improved outcome with biochar amendment appears to be well supported by the literature and is likely to influence additional factors such as compaction resilience, erosion reduction, and possibly filtration and retention capacity.

Compaction influences the physical and chemical performance of biochar amended soils and is of particular importance for roadside stormwater applications. Due to the risk of erosion and damage during rainfall events, compaction is usually a requirement for roadside soils, sometimes up to 85-90% of its capacity to increase slope stability (Le et al. 2020). Therefore, the study of biochar amended soils under compaction conditions is especially important for the context of our study. There were a handful of articles that focused on the effects of compaction on biochar amended soil and water properties which yielded mixed results (Imhoff et al. 2019, Le et al. 2020, Ghavanloughajar et al. 2020, and Yoo et al. 2020). Ghavanloughajar et al. (2020) demonstrated that dry compaction decreased hydraulic conductivity by 44%, but by only 12% under wet conditions, so it is recommended to compact biochar under wet conditions. Le et al.'s (2020) study of compaction and breakage with biochar amended coarse sand (600-850 µm) saw exponential decreases to hydraulic conductivity using softwood, high temp biochar. They found that biochar predominantly breaks by fragmentation or splitting during compaction rather than abrasion.

Imhoff et al. (2019) demonstrated that compaction decreased in field and laboratory columns from two sites for biochar amended sandy loam soils and that amended soils increased water retention and increased infiltration and drainage, which were validated at by flow rates at the field site as well. At their Virginia field site, even greater water retention and compaction resistance was observed. The performance of the field site was maintained for at least three years. Furthermore, Somerville et al.'s (2020) results suggest that in highly degraded urban soils, there was rapid re-compaction after tillage and that there was low bulk density over time (a two-year study) and that there were no changes in the formation of water stable macroaggregates.

Soil losses and erosion rates are related to compaction and are an important consideration for heavily modified or constructed areas, such as the stressed urbanized soils next to roadways. Erosion and soil loss in uncertain rainfall conditions can be dangerous, impede vegetative health, and cause unexpected consequences. Jien and Wang (2013) studied soil losses and erosion rates in their biochar amended and control soils in simulated field conditions. The lowest soil losses occurred in the biochar amended soils and the rate significantly decreased as biochar application rate increased. These results indicate the strong viability of biochar to assist in reducing erosion and improving soil structure and maintenance.

While there were a variety of common soil types covered in the papers reviewed, such as sand, sandy clay, silty loam, clay loam, and sandy loam, we aimed to highlight soils common in North Carolina to inform our study. In North Carolina, the most common type of soils are Cecil soils, which are characterized as clay-y soils**,** and in a range from clay loam to sandy loam, primarily in the Piedmont region of the state. There is also a wide variety of soils in the state in the inner and outer coastal plains as well as the mountainous regions. However, for the context of our review, we chose to highlight comprehensive impacts of biochar on clay soils and the influence of clay soils in relation to biochar. It has been seen that structure, porosity, saturated hydraulic conductivity, and other properties have been improved with biochar amendment to clay soils in simulated stormwater conditions and other types of studies (Omondi et al. 2016, Tian et al. 2019, Somerville et al. 2020, Boehm et al. 2020, and Yoo et al. 2020).

2.2 Reduction in Stormwater Runoff

Saturated hydraulic conductivity (Ksat) is a measure of how easily water can move through soil pores (He et al. 2021, Nakhli et al. 2021). Ksat is an important metric that helps indicate infiltration capacity or runoff potential in a rainfall event. It is usually expected that a high hydraulic conductivity will minimize flood risk (Mohanty et al. 2018) and therefore an increased Ksat would be desirable in stormwater contexts. The effect of biochar on saturated hydraulic conductivity depends on how biochar alters the pore structure of the soil matrix (Nakhli et al. 2021) from its particle size and distribution as well as its hydrophobicity. Additionally, formation of macropores has been seen to be an important mechanism for increased Ksat. The formation of macropores is related to biotic factors, which elevates the importance of understanding field (or field simulated) conditions (Jeffery et al. 2013). Additionally, because of biochar's high porosity and internal pore structure, biochar can increase both saturated hydraulic conductivity as well as storage volume (Mohanty et al. 2018). Omondi et al. (2016) found that biochar amendment had a Ksat increase of 25.2% in their review and Herath (2013), Jeffery et al. (2015), Imhoff and Nakhli (2017), Boehm et al. (2020), and Kuoppamäki et al. (2021), all discussed increases in saturated conductivity with biochar amendment, with many of them in clay soils. Additionally, Jien and Wang (2013) saw a significant increase in saturated hydraulic conductivity, with the values about twice as high as the controls after ~100 days, demonstrating the longevity potential of biochar performance.

However, there have been varied results. For example, conductivity decreases significantly in sand or sandy soils (Jeffery et al. 2015, Ashoori et al. 2019, Ghavanloughajar et al. 2020, and Boehm et al. 2020). Furthermore, Le et al. (2020) saw that small biochar particle sizes caused significant decreases in hydraulic conductivity due to clogging. Therefore, it is recommended to choose coarser and larger particle sized biochars for roadside stormwater use. Additionally, following Nakhli et al. (2021), mixing under wet conditions is recommended for any type of soil and biochar and in the lab and field, which is consistent with the recommendations for compaction discussed earlier.

Due to biochar's porous properties, soil water holding capacity is likely to increase (Boehm et al. 2020). Omondi et al. (2016) found that water holding capacity increased by 15.1%. Kim et al. (2021) saw an increase in water holding capacity in their 60-day drought study for urbanized soils. Herath (2013) did not find statistically significant changes to AWC but did see an increasing trend in the amended soils. However, some studies have commented on the hydrophobicity of biochar acting as a repellant and thus this is worth investigating further.

An additional metric, soil water retention (SWRC), is a related and measurable indicator for how much water is captured in the pores of the soil matrix. An increase in retention not only reduces runoff volume, but also helps create anoxic conditions that assist with denitrification and beneficial microbial communities (Mohanty et al. 2018). Due to the amount of pores biochar has, it would be expected that biochar amendment would increase soil water retention. Liu et al. (2017), Berger et al. (2019), and Imhoff et al. (2019a), and Kuoppamäki et al (2019) all saw increases to SWRC in biochar soils. In an 8-month study on roadside soil drought stress and vegetation, Kim et al. (2021) also saw significantly higher water retention. Hussain et al. (2020) conducted a comprehensive literature review on biochar's effects on SWRC and found that water retention capacity, and water content at a dry state had the most improvements with biochar amendments, which they speculate is due to the changes that occur to the pore system (inter and intra particle pore changes). These results echo multiple studies mentioned above related to the porosity and soil structure benefits of biochar amendment.

Lastly, biochar is often considered to have a high cation exchange capacity (CEC) (Mohanty et al. 2018) due to its negative surface charge. Generally, a high CEC is considered beneficial for K, Mg, and Ca cycling and thus beneficial for vegetative growth (He et al. 2021). Additionally, higher CEC may also help with contaminant removal and buffering. Feedstock type and pyrolysis temperature influence these properties and there are also biochars with a high anion exchange capacity (AEC). For example, grass feedstocks have a greater CEC than woody feedstocks. Additionally, CEC usually decreases as pyrolysis temperature increases, which means that biochar's ability to retain negatively charged chemicals will decrease (Minnesota Pollution Control Agency 2021). Jien and Wang (2013) saw an increase in CEC and pH in biochar amended soils, and that the exchangeable K, Ca, and Mg contents also increased. In Li et al.'s (2019) review of biochar production and properties, they saw a linear decrease in CEC with increasing pyrolysis temperature.

2.3 Improved Water Quality

In the context of stormwater, biochar amendments have exhibited improved outcomes for key areas of water quality: nutrients such as nitrates and phosphates, metals, trace organic compounds (TOrCs) and bacterial contaminants. While also improving soil structure and water capture, biochar can provide multi-benefit outcomes to alleviate total maximum daily load (TMDL) concerns and assist with meeting National Pollution Discharge Elimination Standards (NPDES). Biochar has a high sorption capacity for contaminant removal due to its structure and physicochemical properties that allow for ion exchange, hydrophobic interactions, and increased residence time increasing contaminant removal opportunities (Bock et al. 2015, Ulrich et al. 2015, Bock et al. 2016, Mohanty et. al. 2018, Ashoori et al. 2019). In the following section, we briefly discuss biochar amendment and the removal and reduction of some of these critical water quality concerns.

Roadside runoff tends to carry excess nitrogen which inundates natural systems, causing toxic aquatic conditions and serious events such as algal blooms (Bock et al. 2015, Tian et al. 2019). For example, stormwater runoff contributes 16% of nitrogen to Chesapeake Bay (Tian et al. 2019). Due to the risks associated with non-point source N loading, there are many regulations for TMDLs and increased emphasis on N reduction for stormwater quality management. Many studies have explored nitrogen removal in a variety of N compounds with varied results. Overall, nitrate removal seems more consistent with biochar than ammonium or phosphorus. For example, Berger et al. (2019) demonstrated that in high intensity rainfall events, softwood biochar addition to woodchip biofilters increased the denitrification resilience and capacity of the biofilters due to biochar's ability to decrease dissolved oxygen in pore water and therefore increase water holding capacity and retention of organic carbon and nitrate. These results are consistent with Ulrich et al. (2017) who saw that biochar amendments showed an 86% decrease in TN in column experiments. Kuoppamäki et al. (2021) saw that a 5% biochar application reduced N occu by 44% through compost over a period of two years. Furthermore, Imhoff et al. (2019) demonstrated that biochar could act as a redox agent to promote anaerobic microbial processes, which means that the possibility of microbial denitrification in a bioretention cell with soil, biochar and appropriate microbial communities could be helpful in nitrate removal in stormwater systems.

Based on the literature, biochar removal performance of phosphorus and ammonium compounds were not as significant as nitrates. According to the Minnesota Pollution Control Agency (2021), "biochar is not likely to provide significant phosphorus retention in bioretention practices unless impregnated with cations (e.g., magnesium) during production at relatively low temperatures (e.g., less than 600^{o}C)." Kuoppamäki et al. (2021) found that TP content of biochar was high, but the compost-biochar mix did not leach more than the other treatments, indicating that it was in insoluble form. However, Mohanty et al (2018), Imhoff et al. (2019a), and Yao et al (2012) all demonstrated a decrease in NH_4^+ leaching.

Biochar amendments have also exhibited a high capacity to remove trace organic compounds (TOrCs). Following Ulrich et al. (2015), wood based, high temperature biochars help adsorb TOrCs because of their hydrophobic interactions. In both of her highly cited studies, Ulrich et al. (2015 and 2017) demonstrated significant TOrC removal using high temp pinewood biochar. Boehm et al. (2020) echoes this point to say that higher pyrolysis temperatures will lead to biochars with high surface area, microporosity and hydrophobicity which should aid in the removal of TOrCs, but they also emphasize a concern in the longevity of this outcome due to the variability in biochar production.

In contrast to TOrCs, low temperature biochars are more effective at metal removal (Ulrich et al. 2015). Kargar et al. (2015) saw significantly lower concentrations of Na, Cu, Zn, Cd, and Pb in biochar soil mixtures, but the presence of biochar did not improve the ability of soils to retain these contaminants. Similarly, Kuoppamäki et al (2021) saw that over a two-year period biochar decreased Al, Cu, Ni and Zn significantly. Uchimiya et al. (2011) saw that clay soils have a high Cu sorption capacity, and sandy loam has low Cu sorption capacity and although pecan shell biochar improved sorption in both soils, it had a greater effect on the sandy loam soil. They attributed the improvements seen in the clay soil to electrostatic interactions and complexation of copper by surface functional groups. Although not discussed in detail in this review, complexation and additional surface chemistry properties of biochar are a topic of interest in the literature, especially for contaminant removal.

While we have discussed the possibility of biochar aiding in beneficial microbial communities, there are also harmful bacterial contaminants such as *E. coli* that biochar could assist in retention or filtration. Boehm et al. (2020) found that biochar improved microbial pollutant removal. Le et al. (2020) saw that their columns with small sized biochar had a higher *E. coli* removal capacity, which they attributed to an increase in reduced pore size after compaction.

3.0 Discussion

Despite the presence of extensive and robust scientific studies, there is vast variability in soil type, biochar type, and desired performance outcomes and applications of biochar use as a soil amendment that has proven difficult to glean specific, clear, and field-tested patterns. Additionally, there is also substantially promising evidence that biochar amendment, either incorporated in direct application to roadside soils or in engineered biofiltration media, that SCMs can benefit from biochar. Biochar's high porosity, ability to improve soil structure, and influence on hydraulic conductivity, retention, and adsorption are all promising performance outcomes as based on this literature review. Additionally, some of our key findings include: (i) wet compaction is best across soil and biochar types; (ii) for clay soils, we generally see porosity increase, bulk density decrease, and Ksat increase; (iii) biochar can assist with microbial communities and denitrification; (iv) soil structure is likely to exhibit increased resilience to compaction and erosion with biochar amendment.

Additionally, we observed that the lack of field scale research was the largest gap in biochar amendment studies for stormwater contexts and echo many authors cited in this review to call for longer-term and field studies similar to those by Herath et al. (2013), Imhoff et al. (2017), Imhoff et al. (2019a), and He et al. (2021) to conduct robust field scale projects for roadside amendments. Their work and that of many others indicate promising longevity of biochar benefits for bulk density, porosity, saturated hydraulic conductivity, and other metrics demonstrating the significant potential of biochar.

Many authors also highlighted the relevance of macropore formation as a critical mechanism for soil structure improvement that therefore can subsequently influence other performance metrics such as erosion, compaction resistance, hydraulic conductivity, and bulk density. Therefore, we would recommend further study, classification and understanding of biochar amended soils and changes to macropore formation. In addition to macropore formation, biochar is noted for its high porosity and influence on increasing pore sizes and altering inter- and intra- pore dynamics. Exact changes to these dynamics are reliant on soil type, particle size distribution, and other factors, but play an important yet often understudied, role in changes to soil and biochar physical and chemical properties.

In the context of this study, we only focused on a handful of papers that addressed the impacts on vegetation growth, usually in urbanized and stressed soils (e.g. Yoo et al. 2020, Kim et al. 2020, Somerville et al. 2020). In a future review, we would recommend additional understanding of roadside vegetation patterns and biochar amendment because strong root structures and healthy biota also have a suite of SCM benefits for infiltration, erosion control, compaction mitigation, filtration of metals and nutrients, and runoff mitigation. Therefore, it can be inferred that if biochar enhances root zones and desired vegetation that stormwater management benefits will also increase. Additionally, the studies reviewed here did indicate positive influences of biochar on retention and drought resilience for biochar amended soils, generating potential positive impacts for vegetative health in addition to SCM benefits.

To improve the state of the science, a biochar-soil typification would be extremely beneficial, including an analysis on application rates and most common biofilter designs or direct soil amendment ratios. Amendment percent was discussed and tested at various levels in many studies always had elevated importance in the results. Therefore, a future analysis of application ratios and field implementation volumes and mixtures are an important extension of these studies. Additionally, these mixture ratios would be most valuable also with a greater understanding of a typification of biofilter design or stormwater BMPs for roadside soil amendments. Mohanty et al. (2018) and the Minnesota Pollution Control Agency (2021) discuss GI and LID options, but there is still a disconnect from the field to the lab regarding biochar studies. For example, intricate differences in biochar performance include changes in surface water quality, retention and filtration and then subsurface properties. In many of the bioretention design and stormwater capture systems that were discussed in the literature, there may have been differing benefits in surface water and soil versus subsurface soil and water.

4.0 Conclusions

By investigating the current state of the science in this review, we sought to glean distinct patterns or relationships between biochar characteristics (e.g., feedstock type, pyrolysis temperature, application rate, application context) and performance outcomes (soil and water physical and chemical properties for SCMs and water quality improvement). We discovered that due to the sheer variety of these characteristics and nuances in their relationships, namely also the associated complexity of soil properties, it was difficult to sort out definitive trends. However, we did observe that in stormwater related studies, soft or hard woods were the predominant feedstock types (e.g., pine or birch), which were often produced at mid-range pyrolysis temperatures (400-600C). Furthermore, fine biochars were beneficial for some metal and contaminant removal as compared to medium or coarse biochars but cause increased risk of clogging and decreases to Ksat and other priority indicators for roadside stormwater management. Biochar's high porosity and other characteristics are considered valuable for hydraulic performance outcomes but are contingent upon soil-biochar-application of which there were limited field studies.

Overall, soil structure, compaction and erosion resilience, and hydraulic properties in non-sandy media were usually seen to improve with biochar amendment. Exact performance outcomes were highly variable and contingent on study design, soil composition, biochar composition, and application rate. Due to the changes seen under field circumstances (e.g., vegetation, disruption, compaction, bacterial communities, intermittent rainfall), longitudinal (>16 weeks), site-specific are necessary to determine biochar performance, maintenance, and longevity.

Ultimately, the increasing prevalence of biochar production and application for agricultural and stormwater benefits are promising because they can be a cost-effective and locally sustainable source of carbon enriched recycled organic material to alleviate water and soil issues. Further study and implementation of biochar is recommended, and typification of soil-biochar amendments will aid in understanding a multitude of water and soil related performance measures and outcomes.

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11.B. APPENDIX B: ADDITIONAL RESULTS FOR LABORATORY ANALYSIS

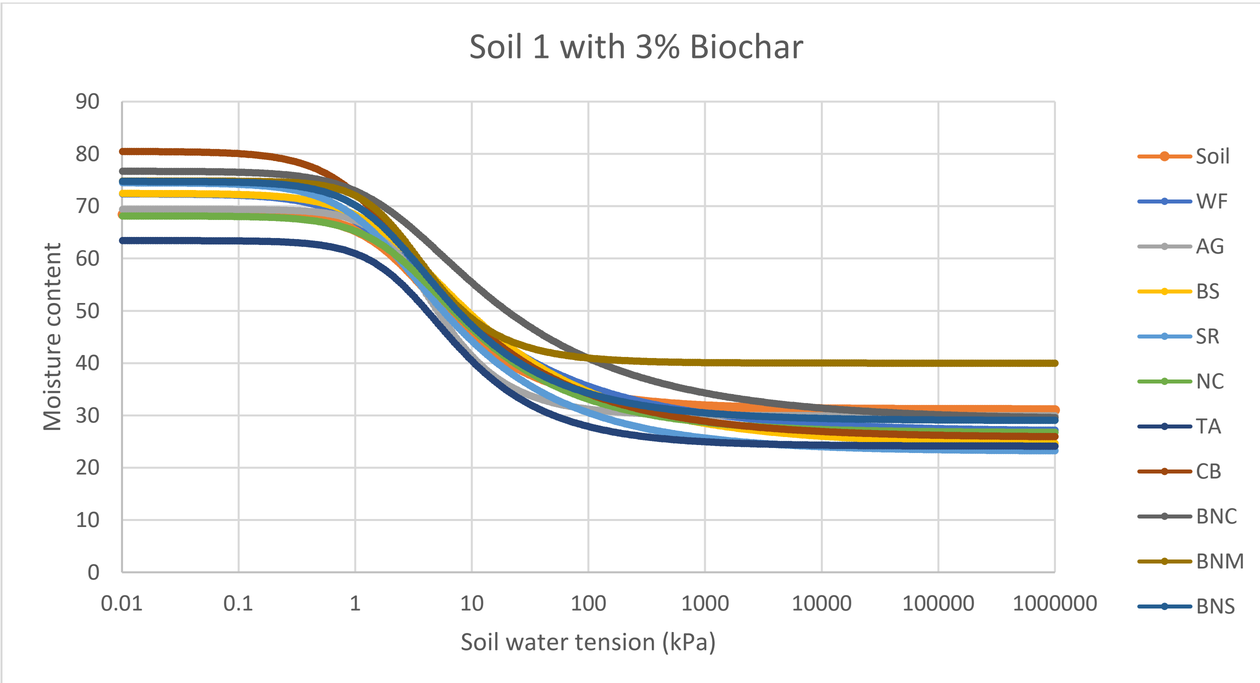


Figure A.1 Water retention capacity of the biochar with soil 1 mixture at 3% biochar content.

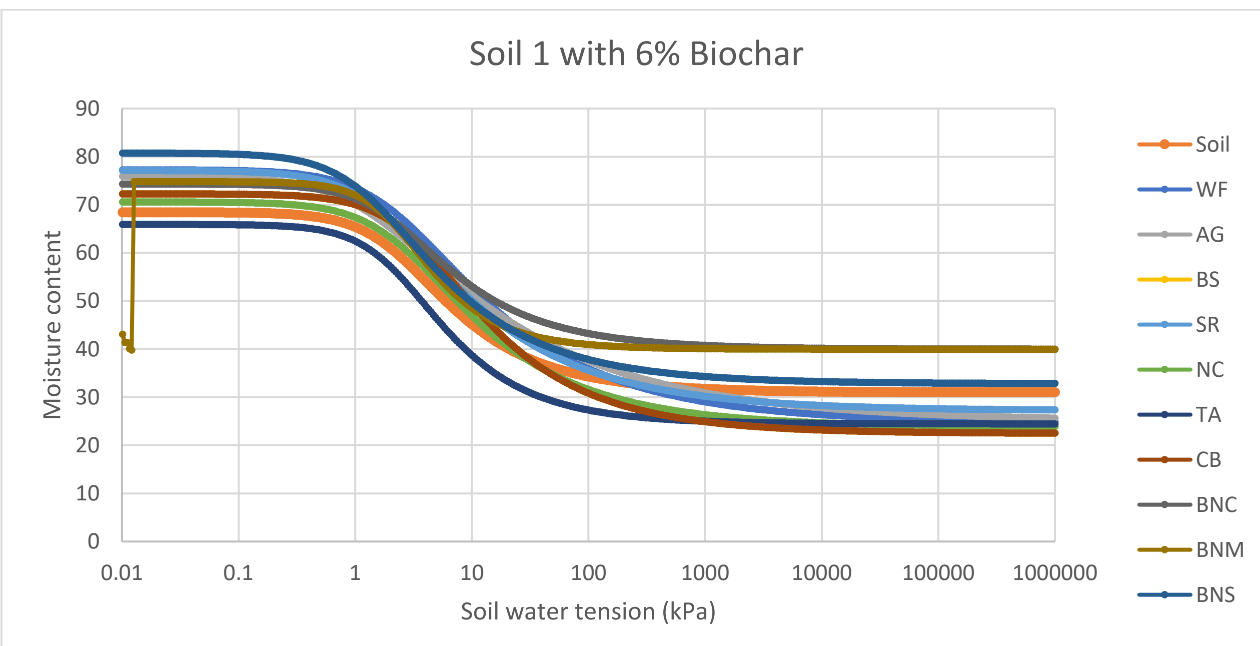


Figure A.2 Water retention capacity of the biochar with soil 1 mixture at 6% biochar content.

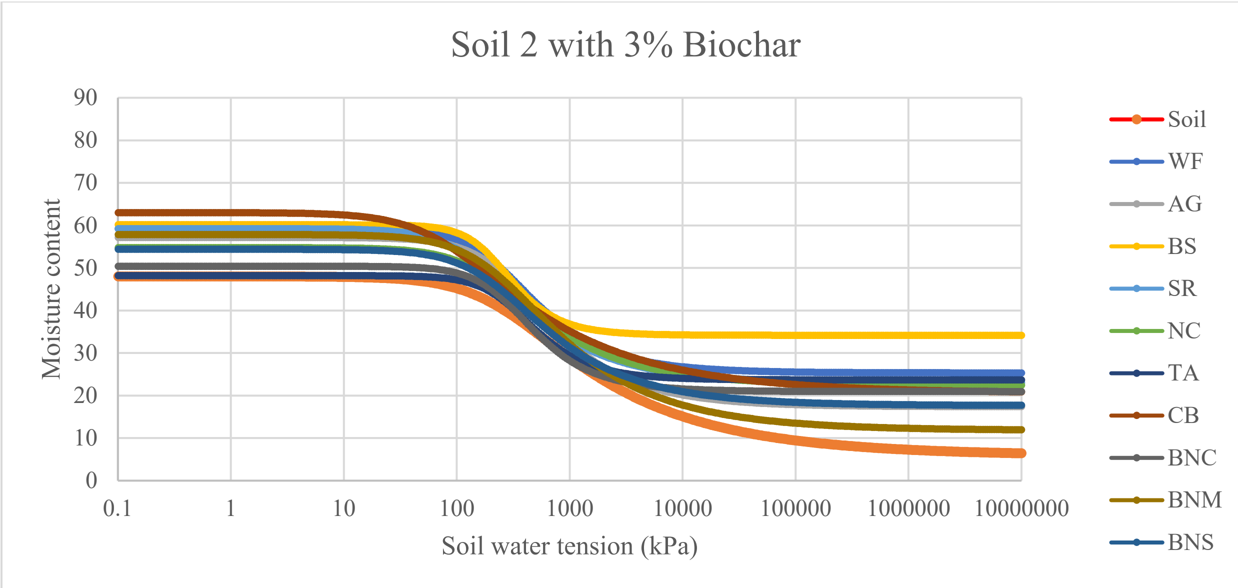


Figure A.3 Water retention capacity of the biochar with soil 2 mixture at 3% biochar content.

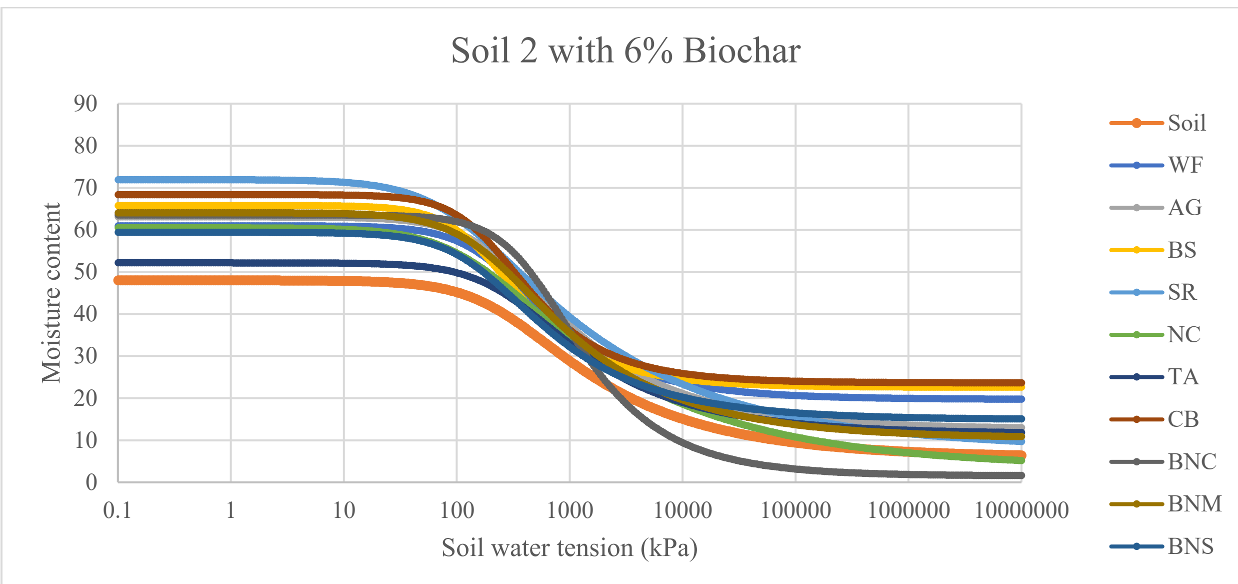


Figure A.4 Water retention capacity of the biochar with soil 2 mixture at 6% biochar content.

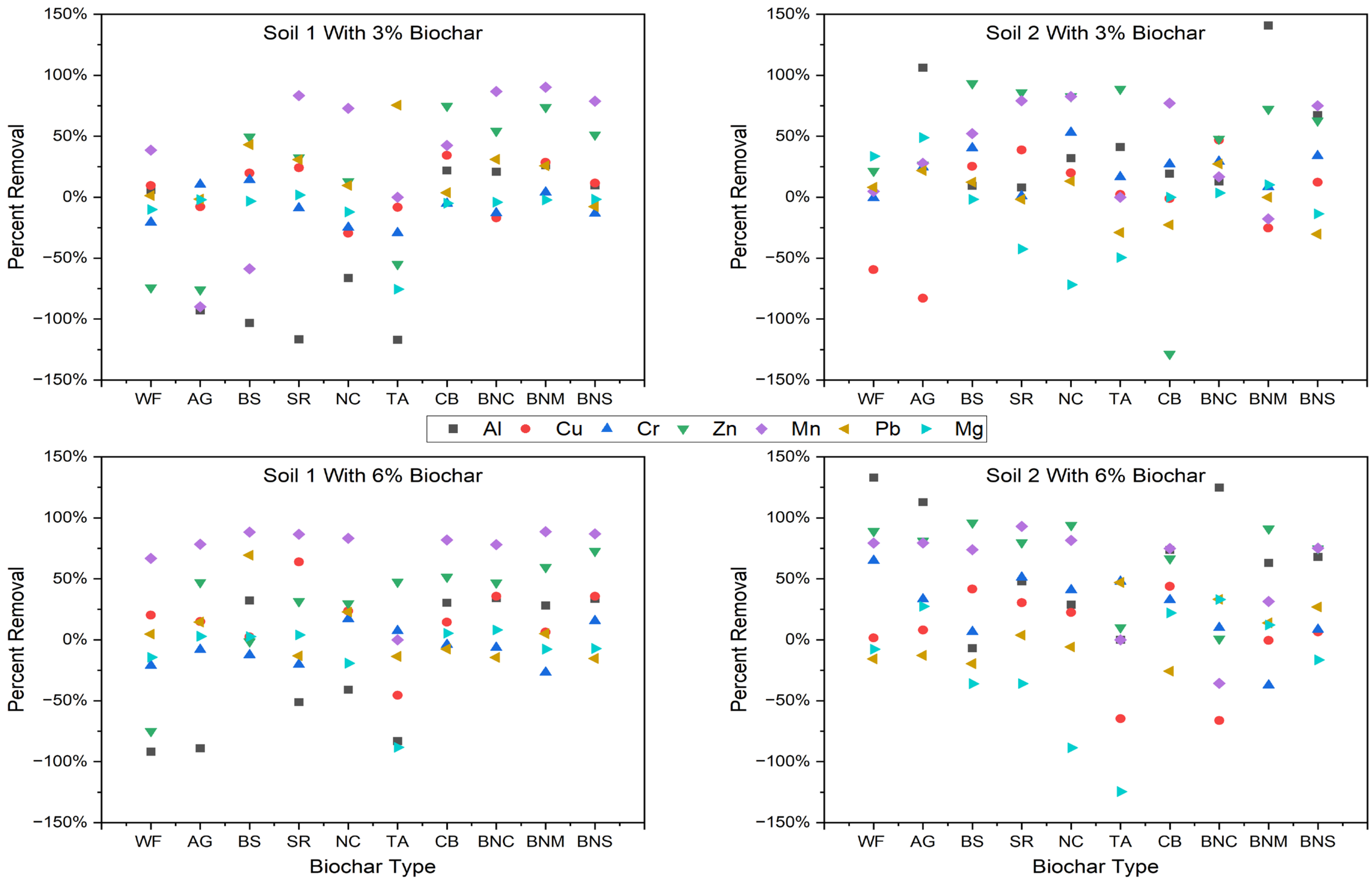


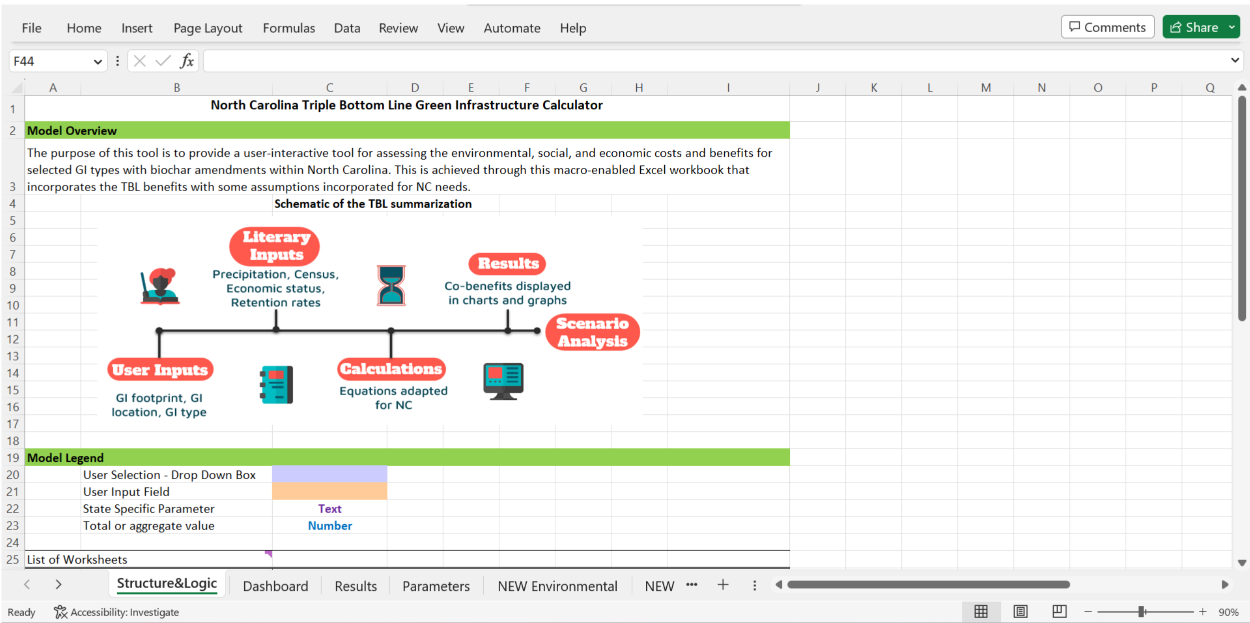
Figure A. 5 Heavy metals removal by different biochar at 3% and 6% biochar content with both soils.

12.C. APPENDIX C: TRIPLE BOTTOM LINE TOOL GUIDANCE

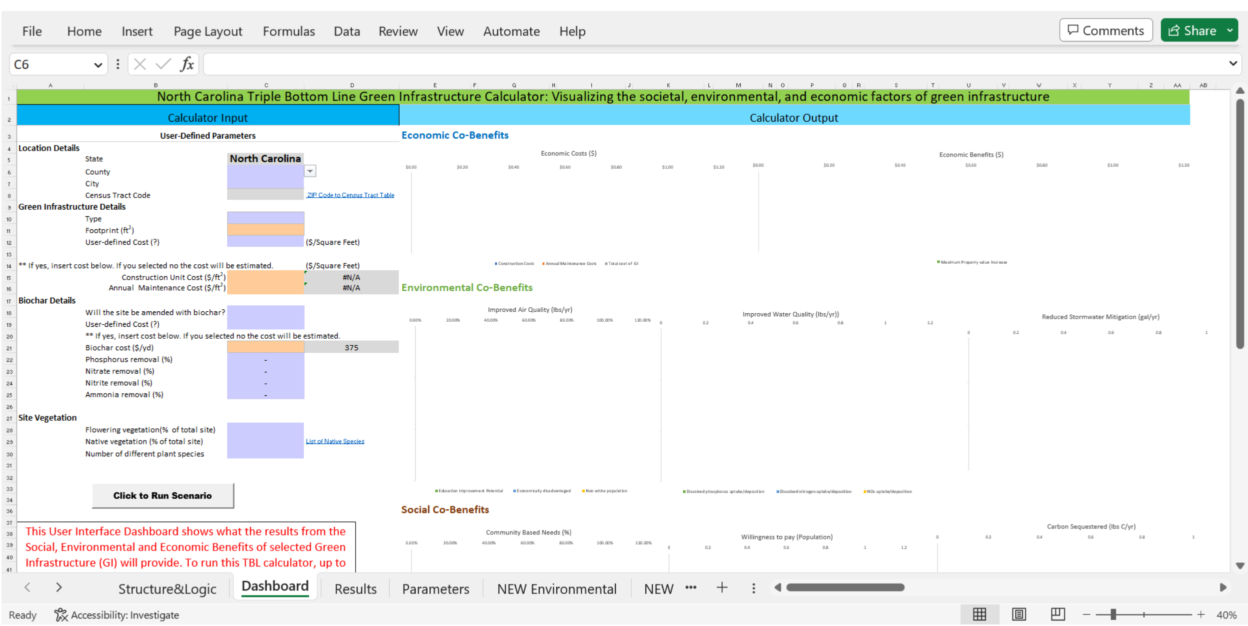
C1. Step-by-Step Guidance

Prior to opening the MS Excel Workbook, make sure that macros are enabled. Visit the following documentation for enabling macros within MS Excel: https://support.microsoft.com/en-us/office/enable-or-disable-macros-in-microsoft-365-files-12b036fd-d140-4e74-b45e-16fed1a7e5c6

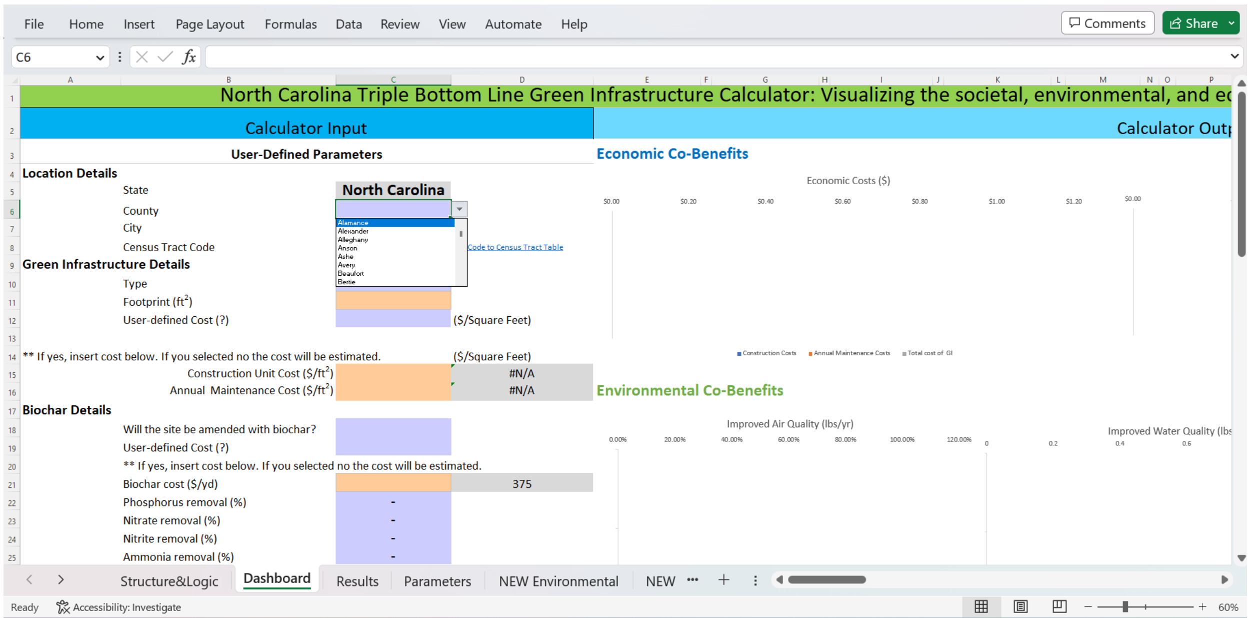
Go to the "Dashboard" section if you'd like to run a scenario.



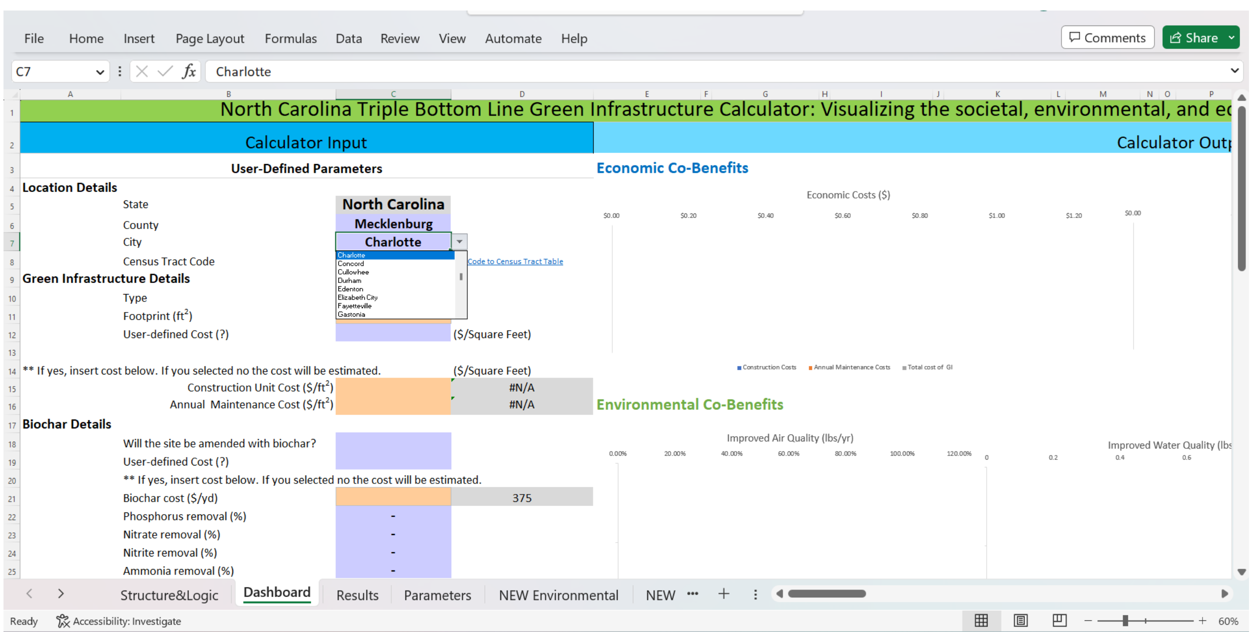
On the Dashboard tab, enter all user inputs. Cells marked in purple are dropdown menus, and those marked in orange are text inputs.



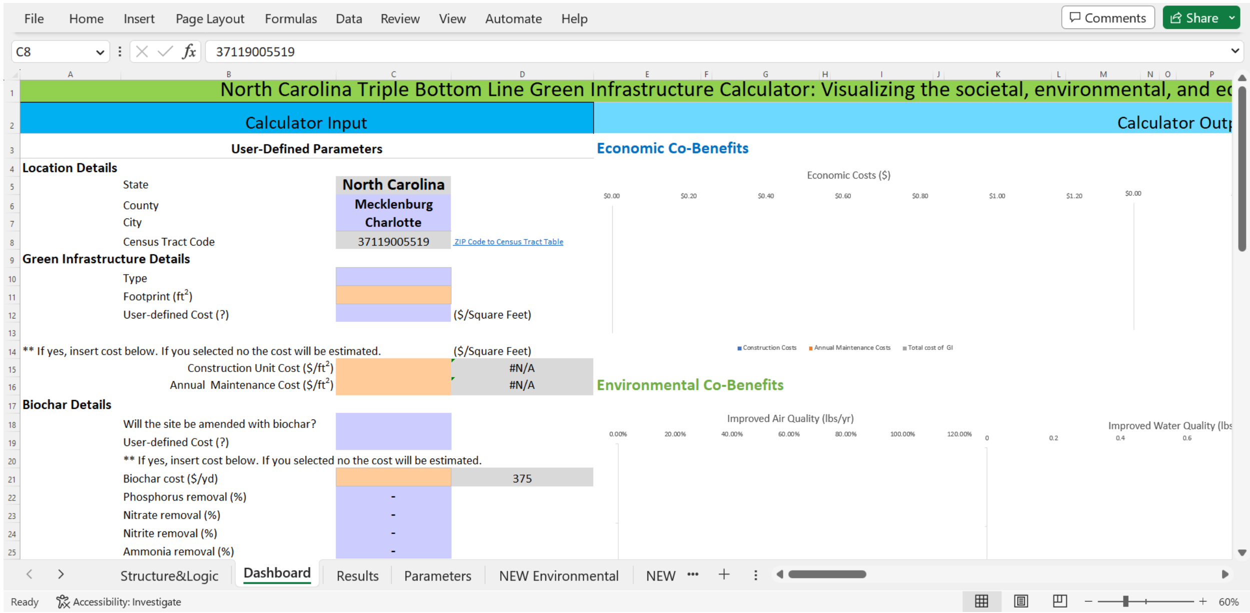
Step 1: Select 'County' drop down menu under location details.



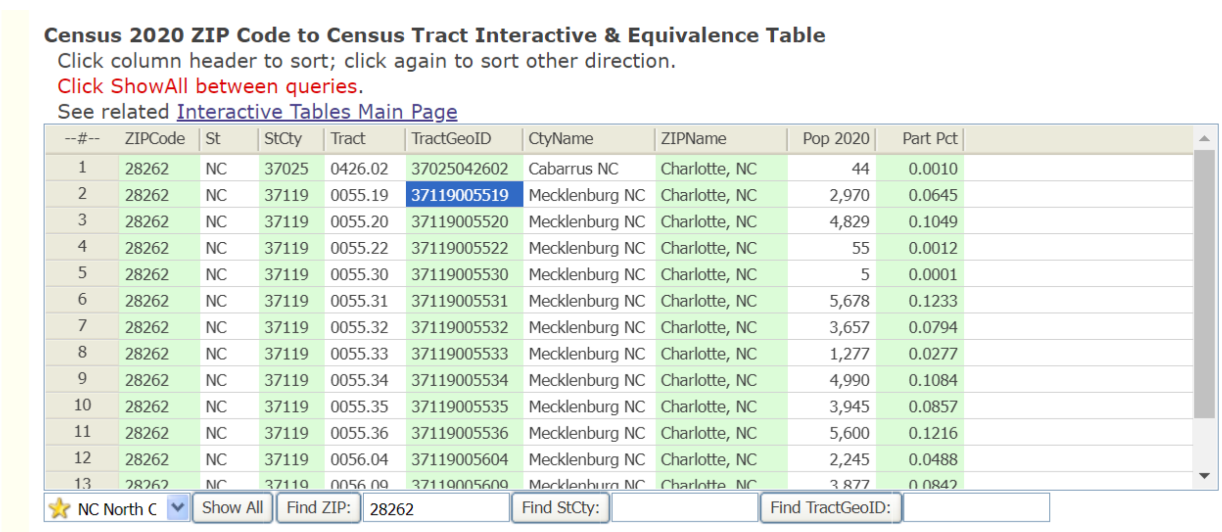
Step 2: Select 'City' drop down menu under location details.



Step 3: Enter ‘Census Tract Code’ in the field under location details.



Census tract codes are accessible here.



Census 2020 ZIP Code to Census Tract Interactive & Equivalence Table

Click column header to sort; click again to sort other direction.

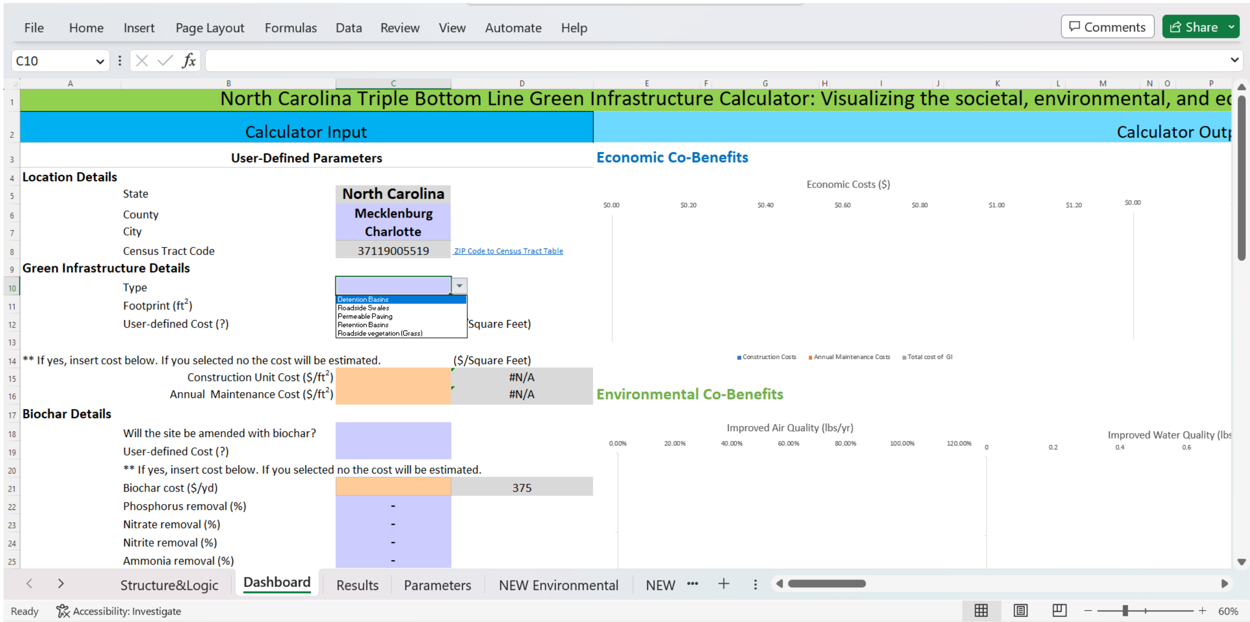
Click ShowAll between queries.

See related Interactive Tables Main Page

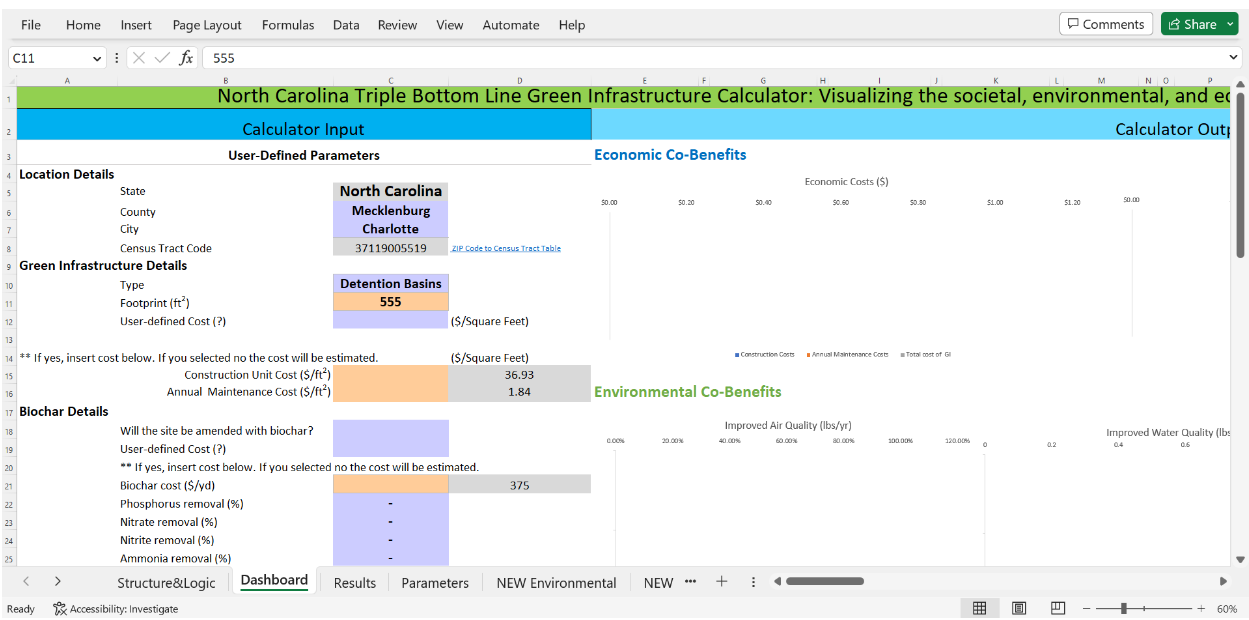
--#--	ZIPCode	St	StCty	Tract	TractGeoID	CtyName	ZIPName	Pop 2020	Part Pct
1	28262	NC	37025	0426.02	37025042602	Cabarrus NC	Charlotte, NC	44	0.0010
2	28262	NC	37119	0055.19	37119005519	Mecklenburg NC	Charlotte, NC	2,970	0.0645
3	28262	NC	37119	0055.20	37119005520	Mecklenburg NC	Charlotte, NC	4,829	0.1049
4	28262	NC	37119	0055.22	37119005522	Mecklenburg NC	Charlotte, NC	55	0.0012
5	28262	NC	37119	0055.30	37119005530	Mecklenburg NC	Charlotte, NC	5	0.0001
6	28262	NC	37119	0055.31	37119005531	Mecklenburg NC	Charlotte, NC	5,678	0.1233
7	28262	NC	37119	0055.32	37119005532	Mecklenburg NC	Charlotte, NC	3,657	0.0794
8	28262	NC	37119	0055.33	37119005533	Mecklenburg NC	Charlotte, NC	1,277	0.0277
9	28262	NC	37119	0055.34	37119005534	Mecklenburg NC	Charlotte, NC	4,990	0.1084
10	28262	NC	37119	0055.35	37119005535	Mecklenburg NC	Charlotte, NC	3,945	0.0857
11	28262	NC	37119	0055.36	37119005536	Mecklenburg NC	Charlotte, NC	5,600	0.1216
12	28262	NC	37119	0056.04	37119005604	Mecklenburg NC	Charlotte, NC	2,245	0.0488
13	28262	NC	37119	0056.09	37119005609	Mecklenburg NC	Charlotte, NC	3,877	0.0842

NC North C | Show All | Find ZIP: 28262 | Find StCty: | Find TractGeoID:

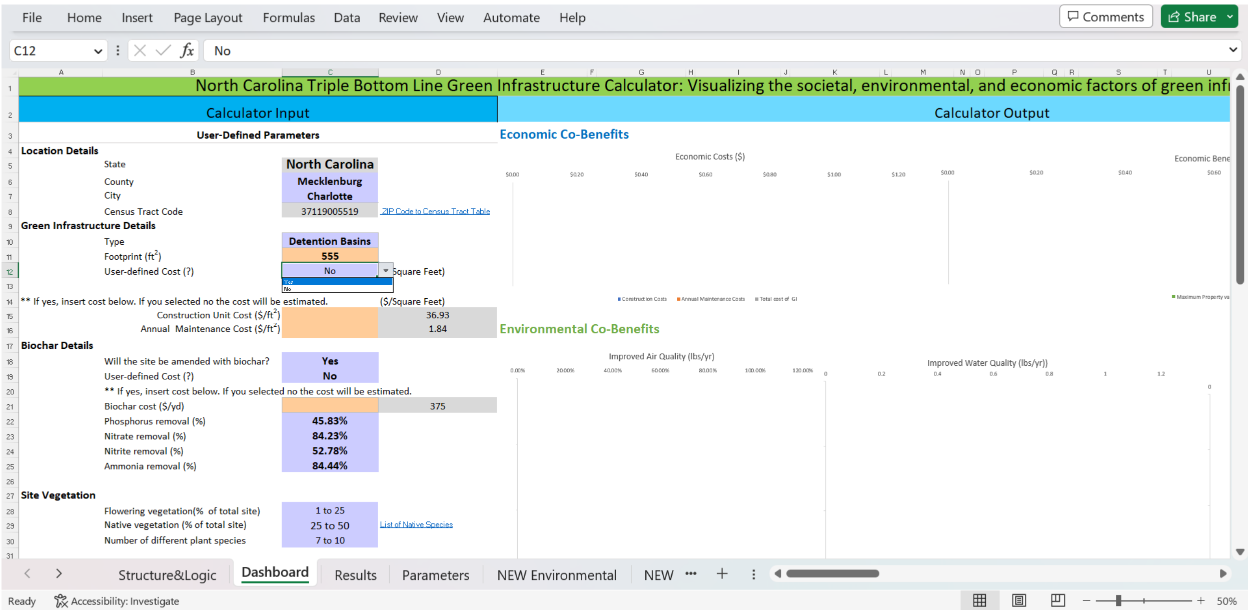
Step 4: Select 'Type' drop down menu under green infrastructure details.



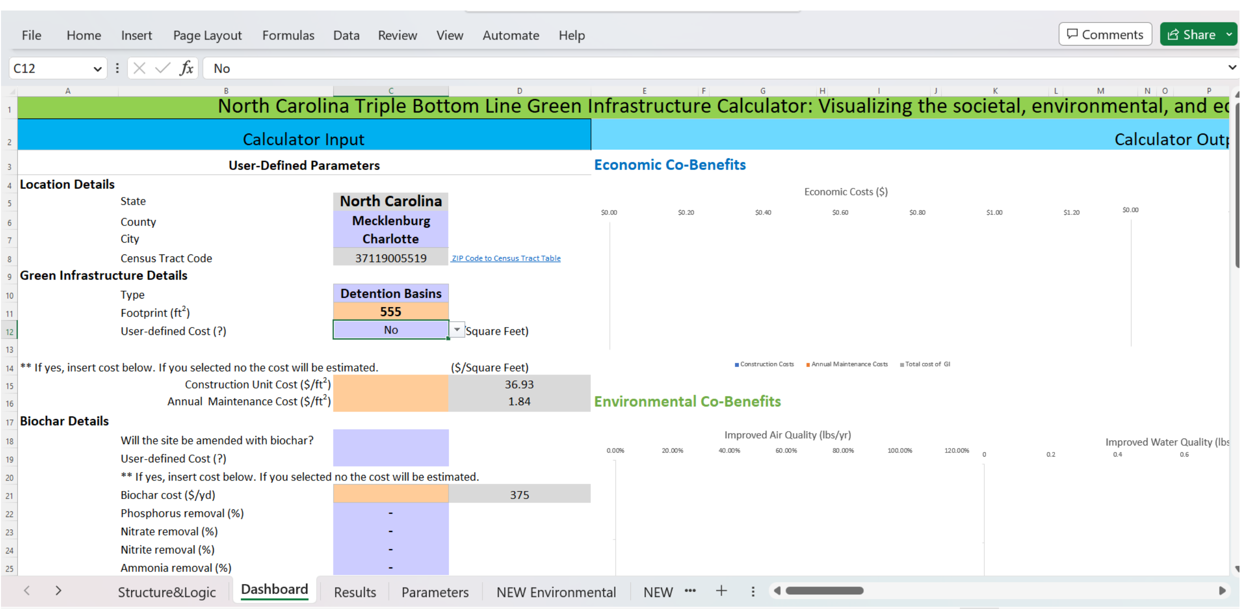
Step 5: Add the green infrastructure's "Footprint" (in square feet) in the cell.



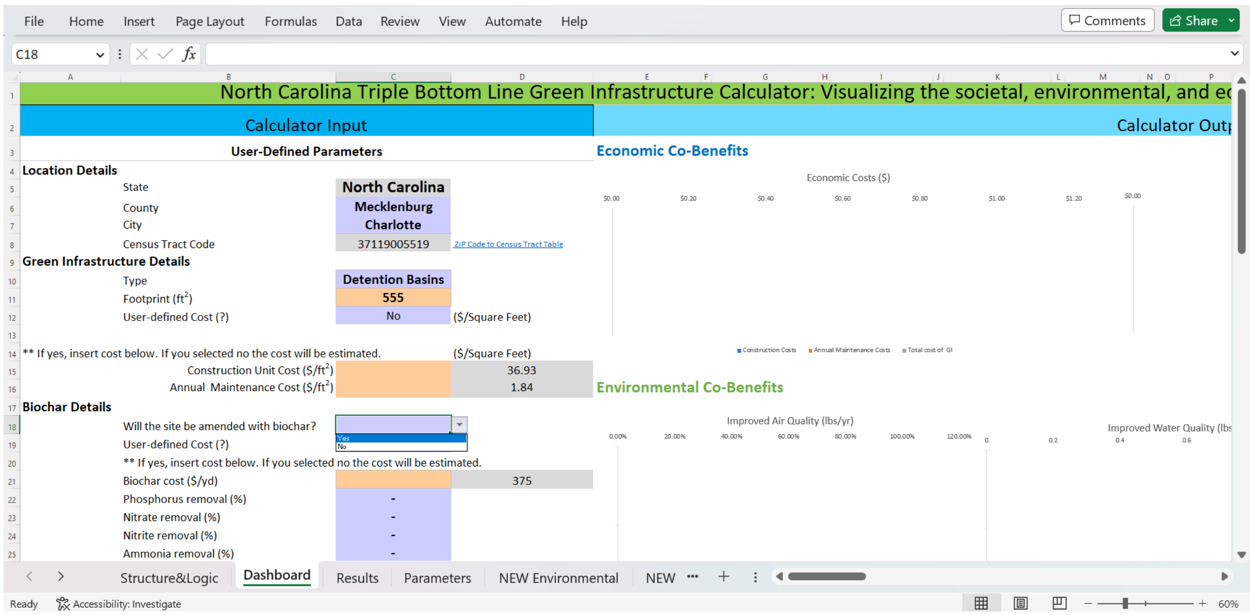
Step 6: Select 'User-Defined Cost' from drop down menu. This is notating whether or not you'd like to define your own costs or use the workbook preset values.



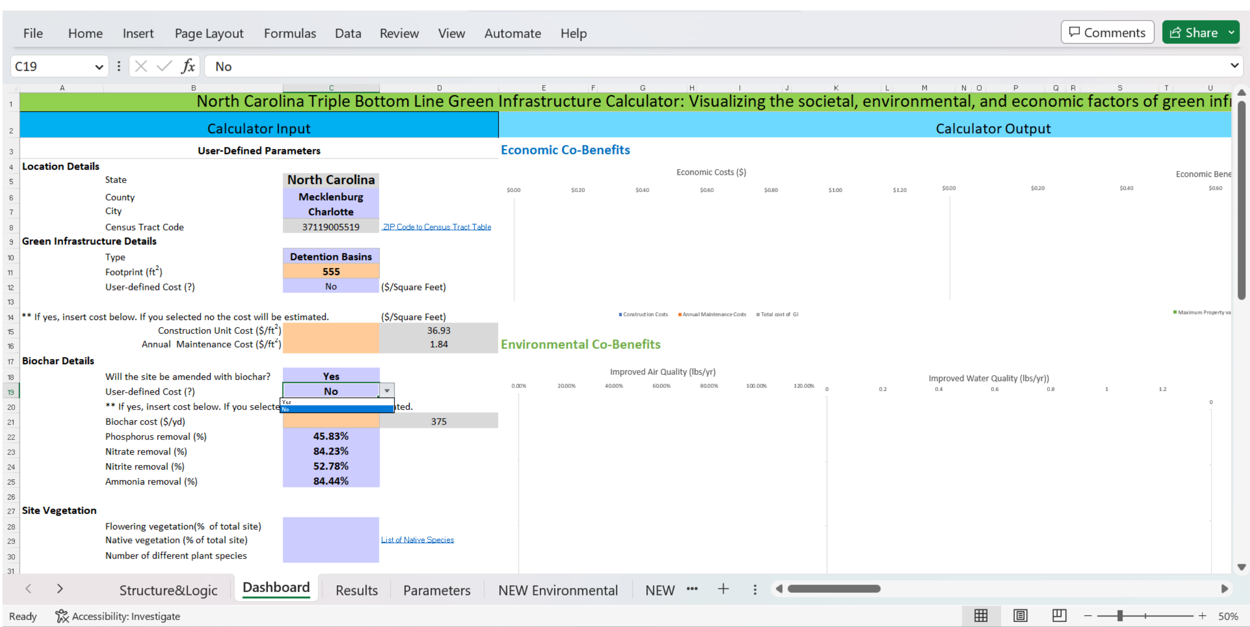
If selection is 'YES" then you may enter values in user defined cells. If selection is 'NO' then preset values in the model will be selected.



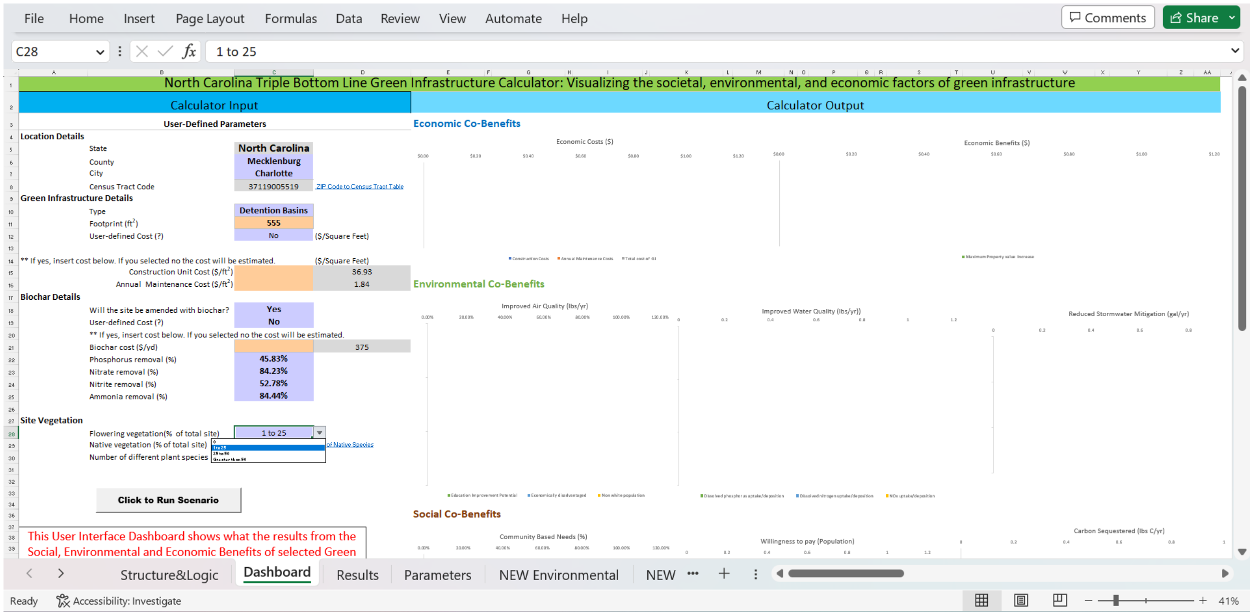
Step 7: Select 'Biochar inclusion' drop down menu under biochar details. The scenario will include a GI amended with biochar (at 6%) if "YES" is chosen.



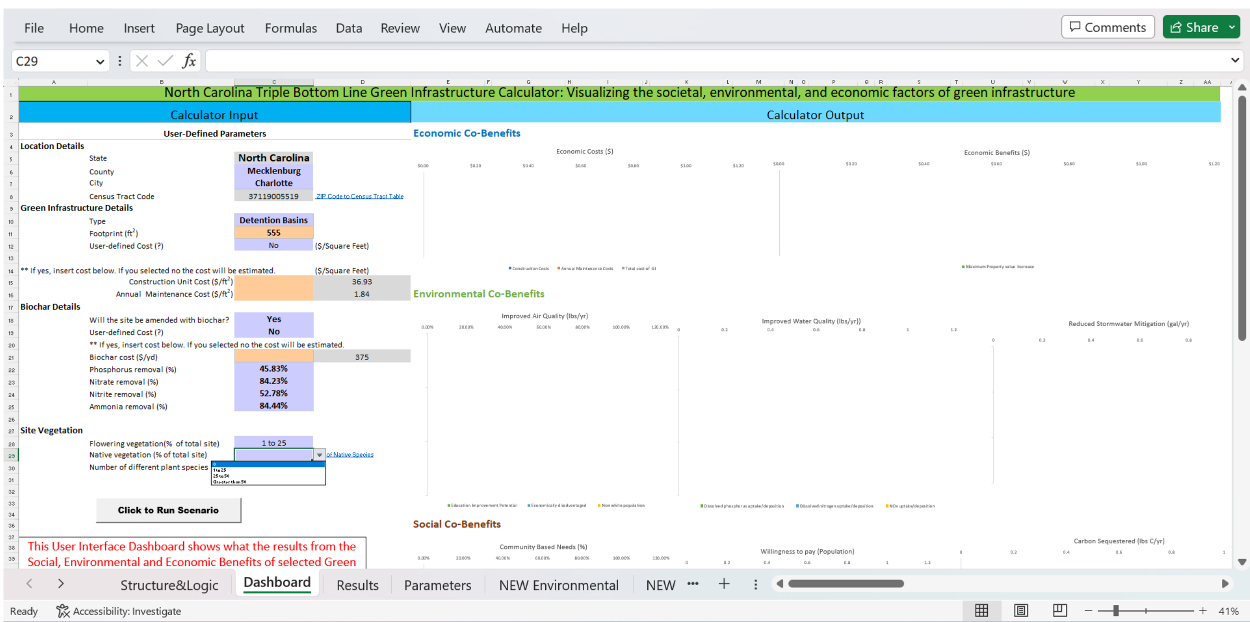
Cost for biochar can be either user-defined or preset. If selection is 'YES" then you may enter values in user defined cells. If selection is 'NO' then preset values in the model will be selected.



Step 8: Select 'Flowering vegetation' drop down menu under Site Vegetation.

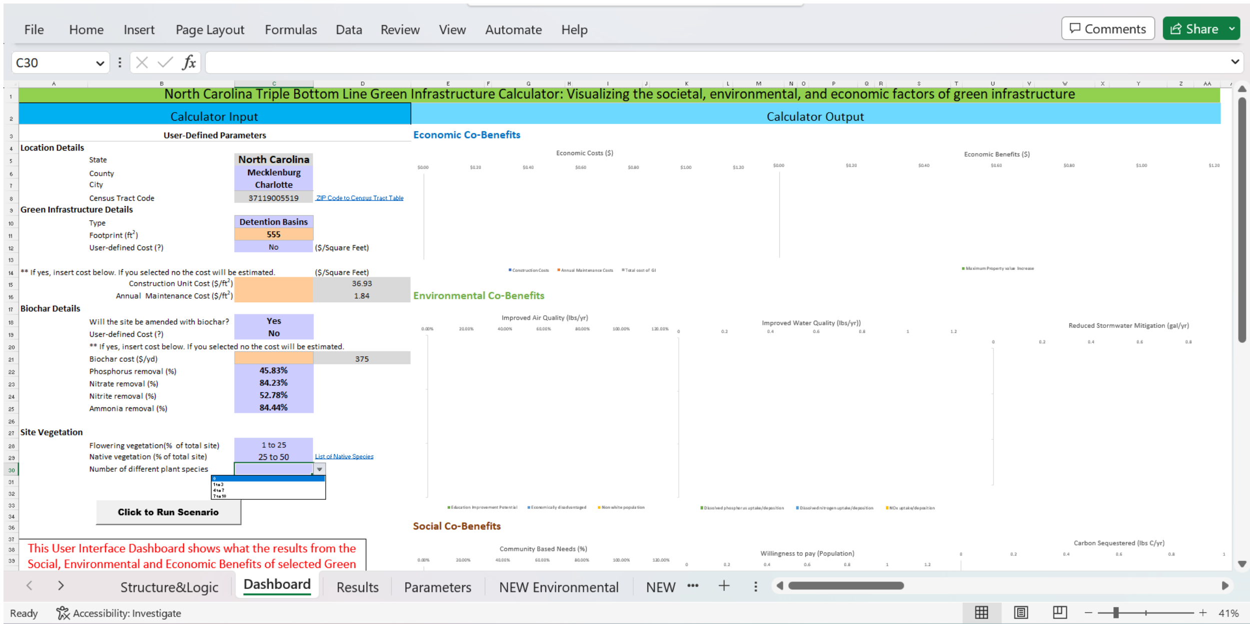


Step 9: Select 'Native vegetation drop down menu under Site Vegetation. Some list of native species can be accessed here.

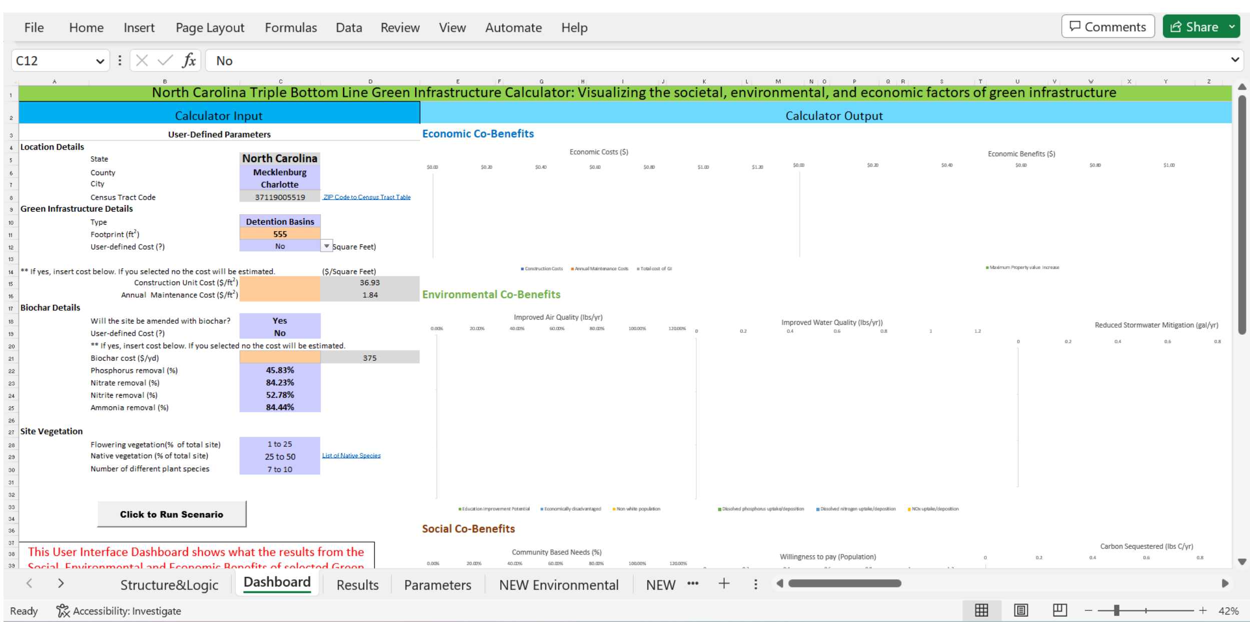


S

Step 10: Select 'Number of different plant species 'drop down menu under Site Vegetation.



Step 11: To generate results, click 'run scenario'. Note that the dashboard will only display up to three scenarios, after which the values will reset. Make sure to copy the values over to another file prior to running the fourth scenario. Results will populate in the calculator output section to the right.

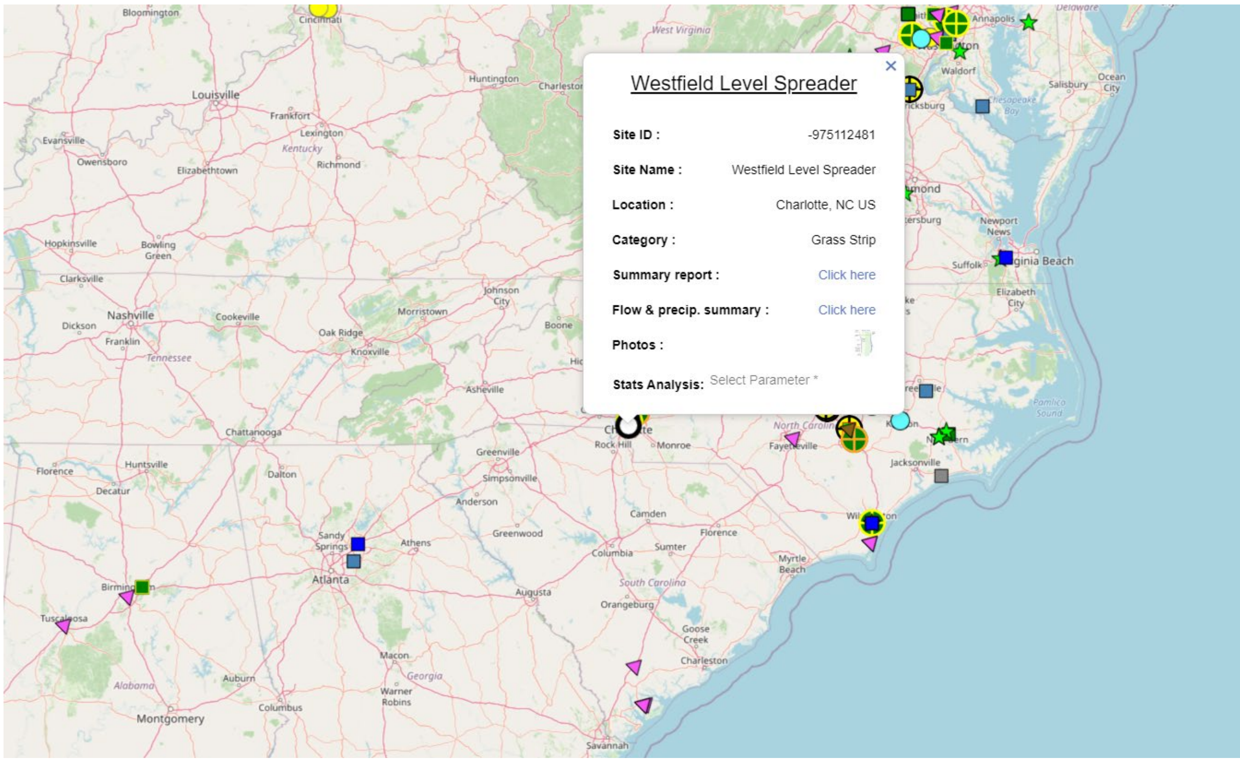


Step 12: In addition to the visualized results on the dashboard, you can find the results in tabular form within the Results tab.

		Scenario 1	Scenario 2	Scenario 3
	Parameter	Value	Value	Value
Environmental	Carbon Sequestered	309.5970284	2491.011485	377.2103389
	Phosphorus deposition	-0.382849738	4.460918823	-0.61805855
	Nitrogen deposition	1.011301195	15.22377059	0.969503608
	Ammonia deposition	71.97032166	1140.169759	69.51844712
	Dissolved phosphorus uptake/deposition	-130.0244394	229.4186823	-26.66134921
	Dissolved nitrogen uptake/deposition	1.444715993	11.32931765	2.132907937
	NOx uptake/deposition	87.04608332	842.5925696	62.064766
	Reduced Stormwater Mitigation(gal)	865576	4242350	1452152
	Additional storm water volume retention with biochar (gal)	1591133	17676455	2160941
Social	Willingness to pay (population)	624247	120353	76105
	Aesthetic Potential	NO	NO	NO
	Asthma Incidence Reduction Potential	7.80%	7.60%	7.50%
	Education Improvement Potential	31.52%	2.33%	10.56%
	Economically disadvantaged	9.11%	31.11%	12.83%
	Non white population	55.80%	14.30%	27.31%
	Potential to improve lack of green space	YES	YES	YES
Economic	Construction Costs	$65,553.00	$27,825,795.00	$4,213,621.00
	Annual Maintenance Costs	$11,238.00	$1,386,393.00	$209,940.00
	Total cost of GI	$76,791.00	$29,212,188.00	$4,423,561.00
	Reduced Stormwater Treatment Needs	$302,952.00	$2,206,022.00	$406,603.00
	Reduced Water Treatment Needs with Biochar	$556,897.00	$9,191,757.00	$605,064.00
	Maximum Property value Increase	$1,579.30	$0.00	$1,862.56
		$2,868.00	$926.00	$3,383.00
Ecosystem	**Ecosystem**			
	Pollinator Support	Likely	Possible	Possible
	Native Habitat Support	Possible	Possible	Likely
	Bio Diversity Support	Likely	Likely	Very Likely

C2. Example Workbook Scenarios for Demonstration Purposes

Scenario-1



Description	Biofilter - Grass Strip	BMP Type	Grass Strip (BI)
Test Site	Westfield Level Spreader	BMP Category	BI
Location	Charlotte, NC 28209, US	Install Date	2005-10-01

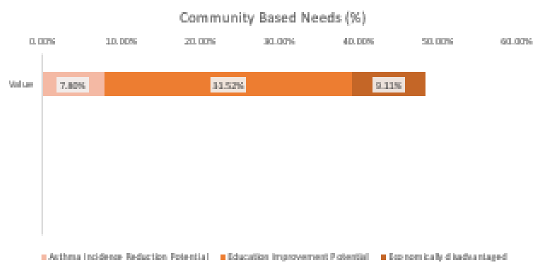
Watershed Characteristics		Transportation Characteristics	
EPA Rain Zone	2	Activity Type	Not Applicable
Watershed Name	Little Sugar Creek Watershed	AADT	N/A
Watershed Type	Test	Lane Count	N/A
Total Watershed Area	0.870	Highway Conditions	N/A
Area Unit	ha	Highway Maintenance	N/A
Percent Impervious	45.0	Road Type	N/A
Soil Group	N/A	Resurfacing	N/A
Watershed Description	Most developed watershed in Mecklenburg county (mostly residential)	Shoulder	N/A
Land Use Description	Medium Density Residential	Winter Maintenance	N/A
Vegetation Description	N/A	Conveyance	N/A

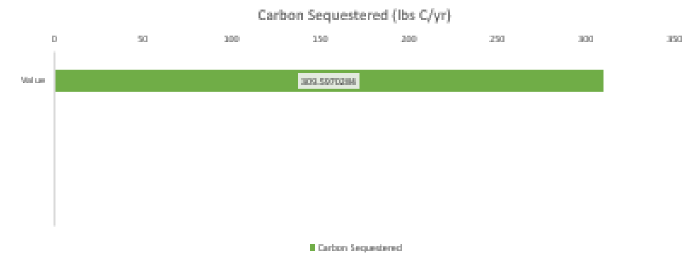
BMP Cost Informatiom	
Annual Maintenance Cost	N/A
Capital Cost	N/A

Scenario 1 Inputs	
Location Details: County City Census Tract Code	 Mecklenburg Charlotte 37119005519
Green infrastructure Details: Type Footprint (ft^2) User-defined cost	 Roadside Vegetation 93646.02 No
Biochar Details: Will the site be amended with biochar? User-defined cost	 Yes No
Site Vegetation: Flowering Vegetation Native Vegetation Number of different plant species	 25 to 50 1 to 25 4 to 7

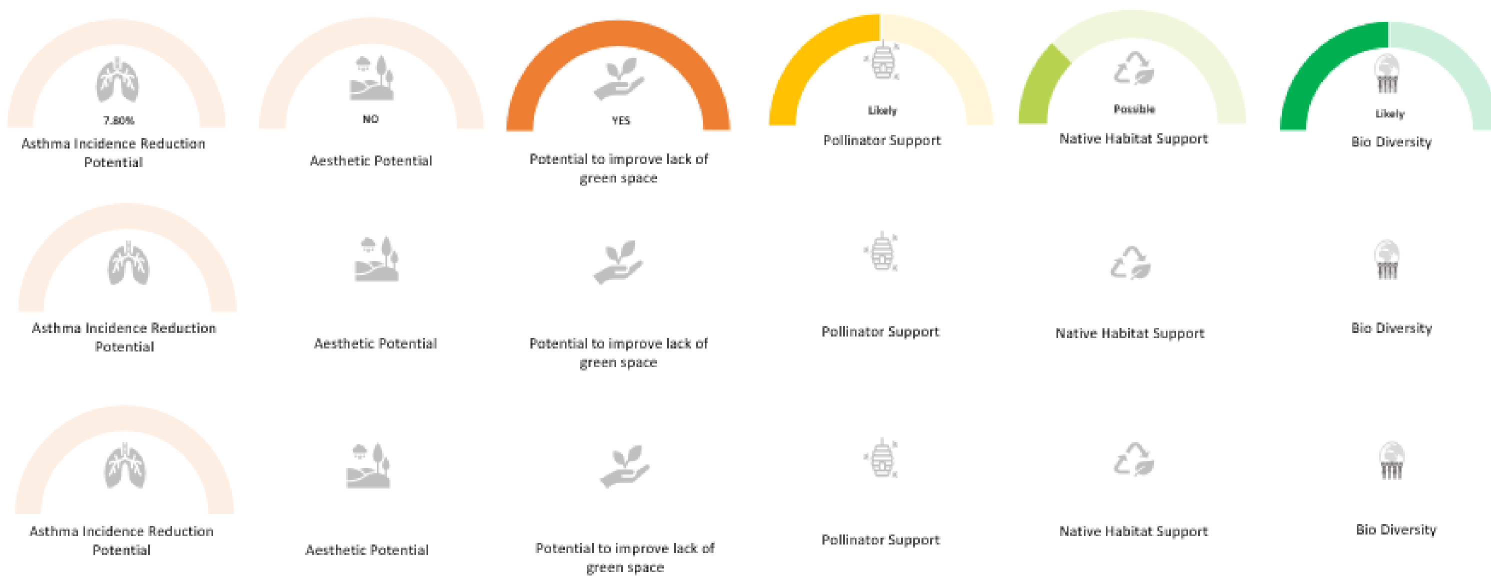
Scenario 1 Results:

Social Co-Benefits

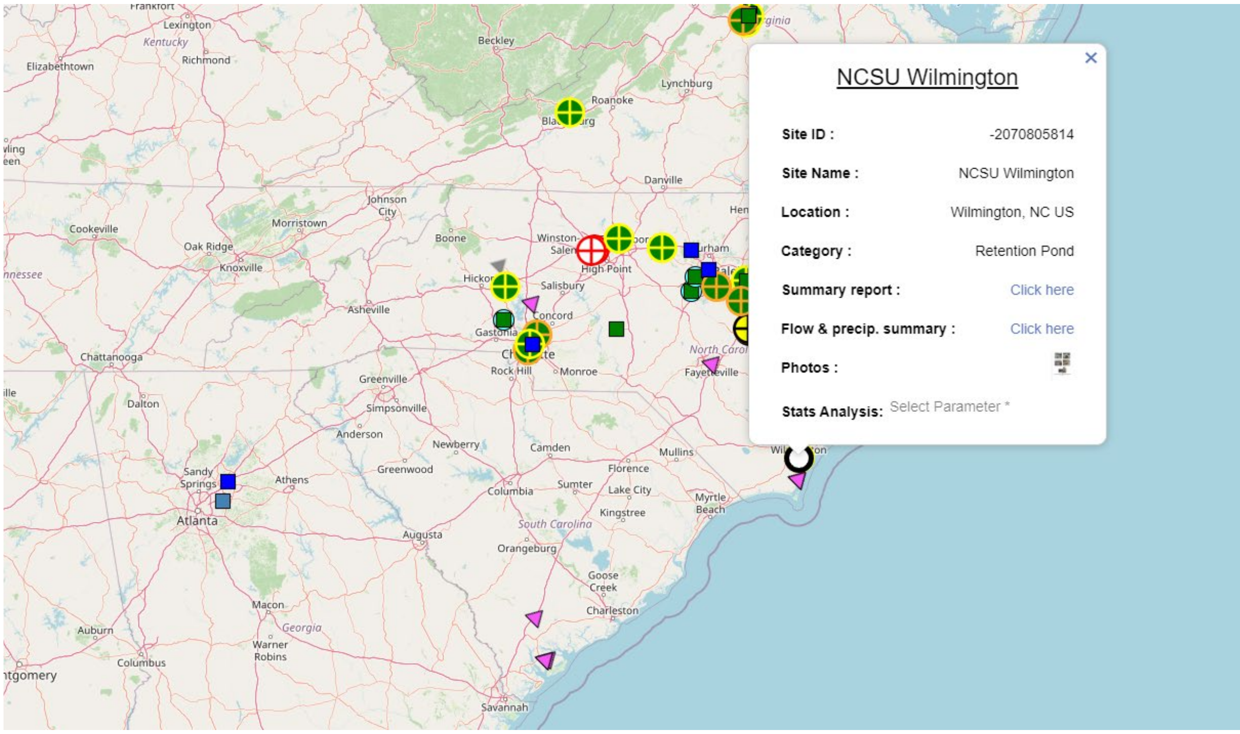




Scenario 1



Scenario-2



Description	Retention Pond (Wet) - Surface Pond With a Permanent Pool	BMP Type	Retention Pond (RP)
Test Site	NCSU Wilmington	BMP Category	RP
Location	Wilmington, NC, US	Install Date	1999-06-01

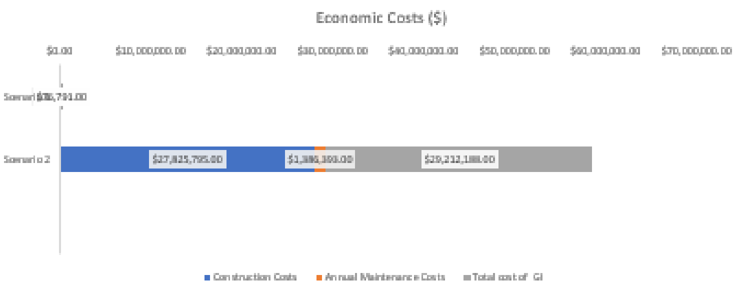
Watershed Characteristics		Transportation Characteristics	
EPA Rain Zone	2	Activity Type	Not Applicable
Watershed Name	Wet Pond 1	AADT	N/A
Watershed Type	Test	Lane Count	N/A
Total Watershed Area	7.00	Highway Conditions	N/A
Area Unit	ha	Highway Maintenance	N/A
Percent Impervious	45.0	Road Type	N/A
Soil Group	B	Resurfacing	N/A
Watershed Description	Wet Pond 1 was located in a residential medium density neighborhood with a watershed area of approximately 7 ha.	Shoulder	N/A
Land Use Description	Multi-Family Residential	Winter Maintenance	N/A
Vegetation Description	N/A	Conveyance	N/A

Scenario 2 Inputs	
Location Details:	
County	New Hanover
City	Wilmington
Census Tract Code	37129011502
Green infrastructure Details:	
Type	Retention Pond
Footprint (ft^2)	753474
User-defined cost	No
Biochar Details:	
Will the site be amended with biochar?	Yes
User-defined cost	No
Site Vegetation:	
Flowering Vegetation	1 to 25
Native Vegetation	1 to 25
Number of different plant species	4 to 7

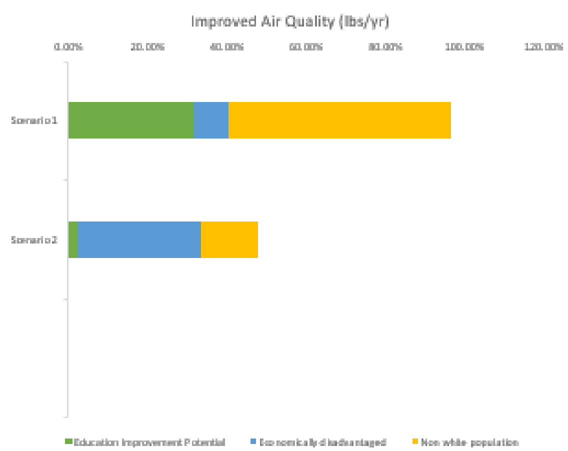
Scenario 2 Results:

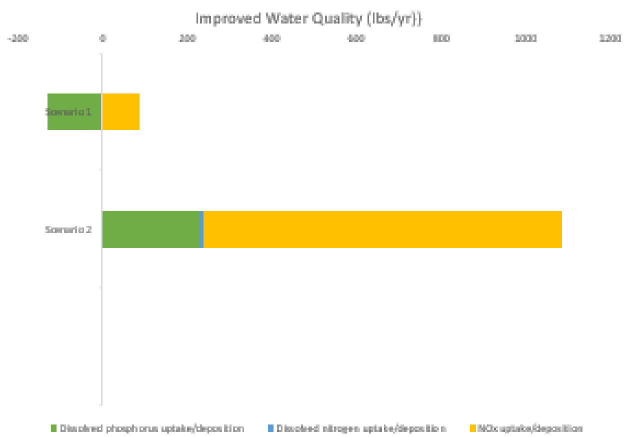
Calculator Output

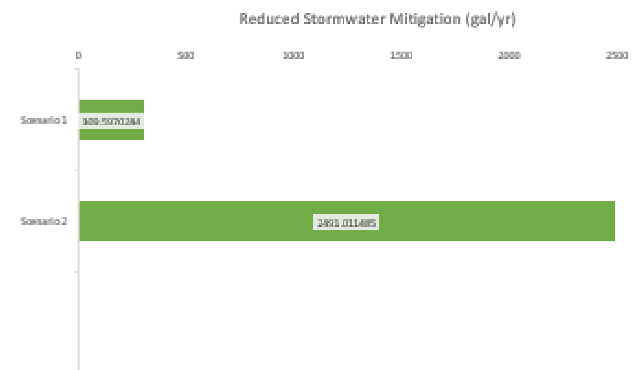
Economic Co-Benefits



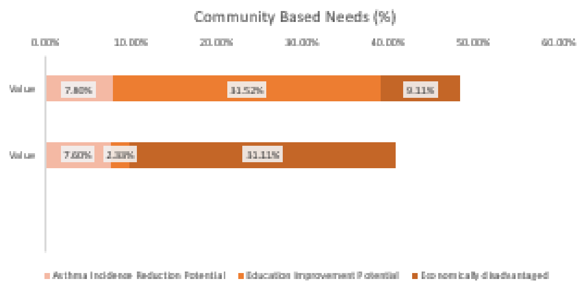
Environmental Co-Benefits

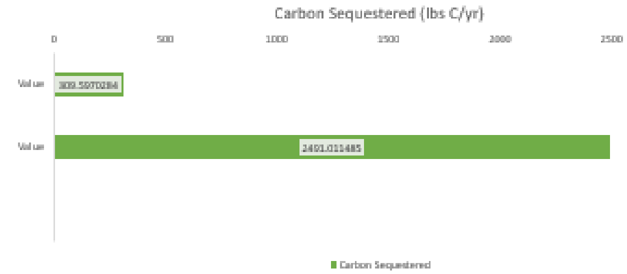


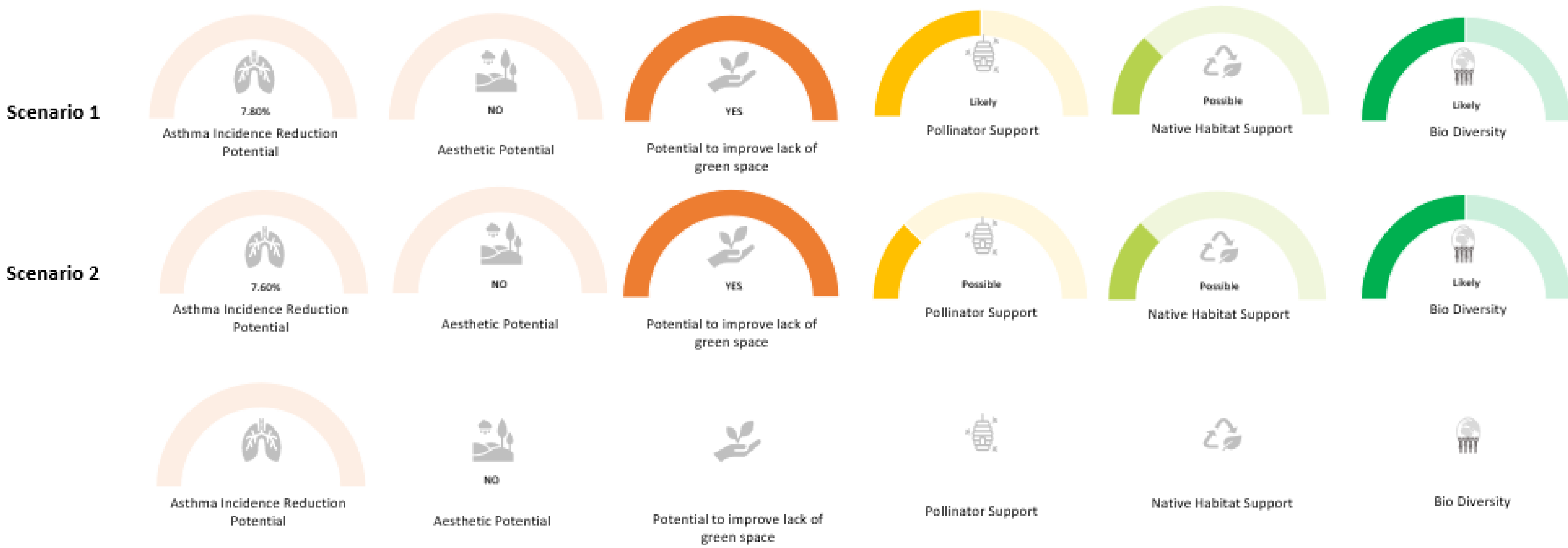




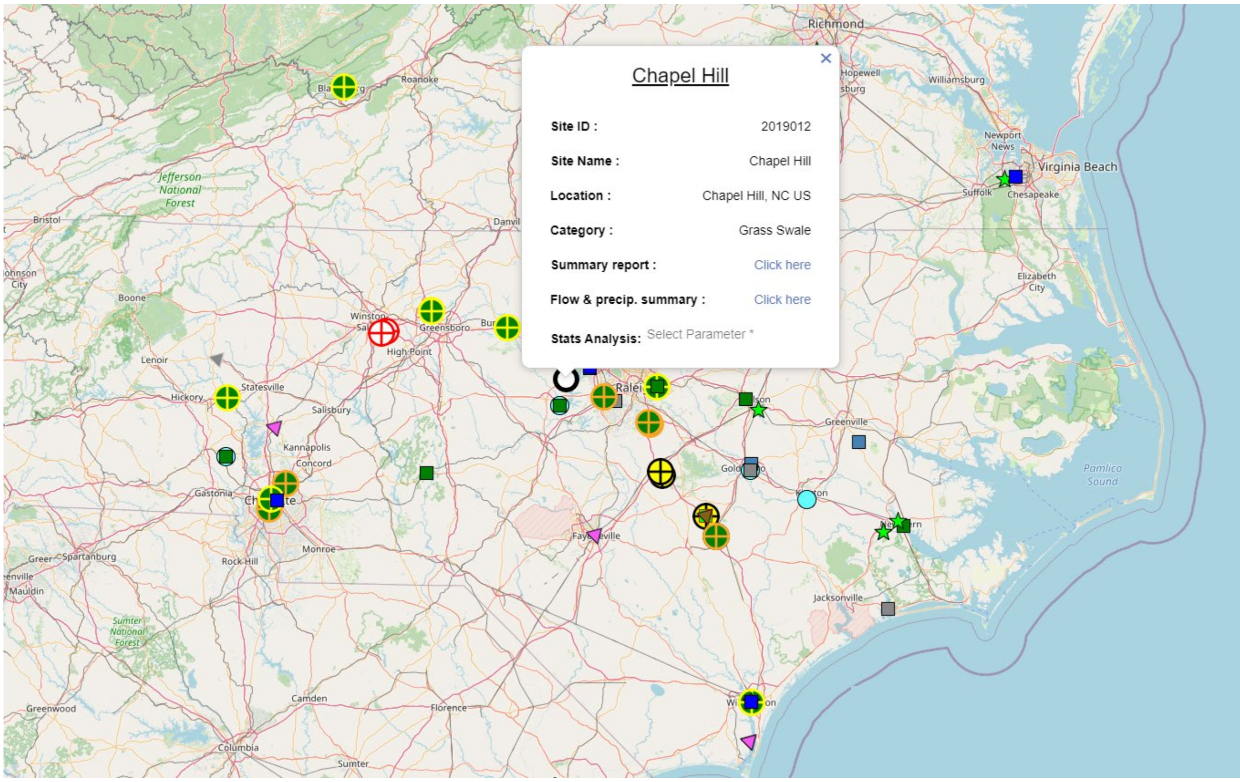
Social Co-Benefits







Scenario-3



Description	Biofilter - Grass Swale	BMP Type	Grass Swale (BS)
Test Site	Chapel Hill	BMP Category	BS
Location	Chapel Hill, NC 27517, US	Install Date	N/A

Watershed Characteristics		Transportation Characteristics	
EPA Rain Zone	2	Activity Type	Highway
Watershed Name	JLN-D	AADT	2,600
Watershed Type	Test	Lane Count	2.0
Total Watershed Area	1.06	Highway Conditions	N/A
Area Unit	ha	Highway Maintenance	N/A
Percent Impervious	47.0	Road Type	N/A
Soil Group	N/A	Resurfacing	N/A
Watershed Description	Water drains from SR 1717, a two-lane paved road carrying an average daily traffic count of 2,600 vehicles. Surface runoff from a roadway segment of 10,710 ft2 flows laterally into a 12,317 ft2 vegetated roadside ditch.	Shoulder	N/A
Land Use Description	Highway, open space	Winter Maintenance	N/A
Vegetation Description	N/A	Conveyance	N/A

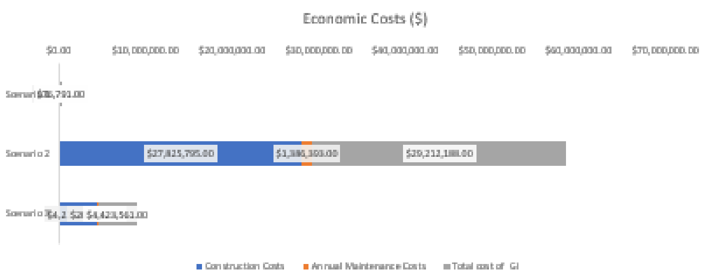
BMP Cost Informatiom	
Annual Maintenance Cost	N/A
Capital Cost	N/A

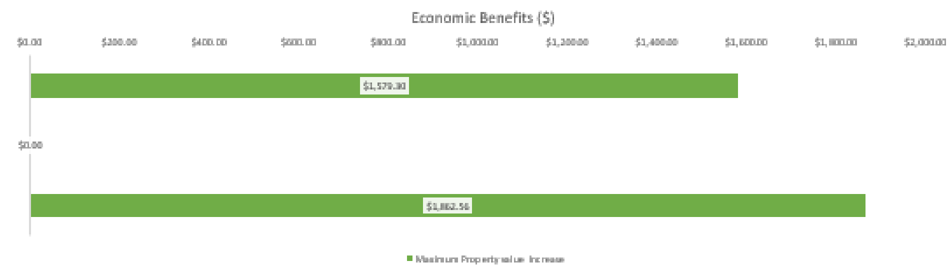
Scenario 3	
Location Details: County City Census Tract Code	 Orange Durham 37063002019
Green infrastructure Details: Type Footprint (ft^2) User-defined cost	 Swale 114097.5 No
Biochar Details: Will the site be amended with biochar? User-defined cost	 Yes No
Site Vegetation: Flowering Vegetation Native Vegetation Number of different plant species	 1 to 25 25 to 50 7 to 10

Scenario 3 Results:

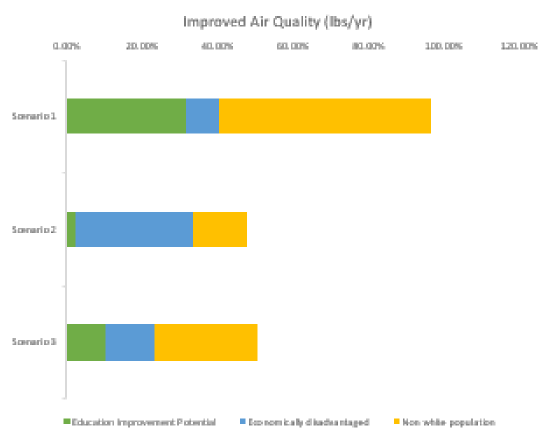
Calculator Output

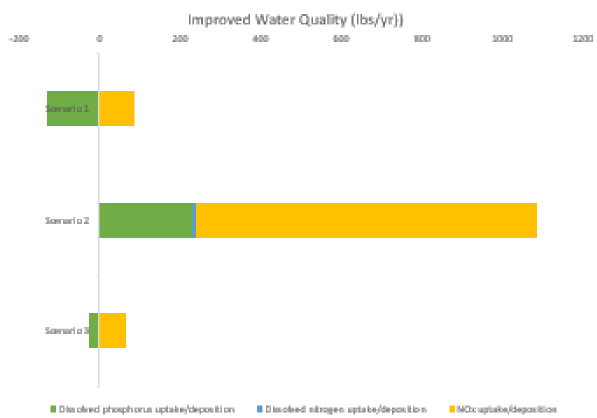
Economic Co-Benefits

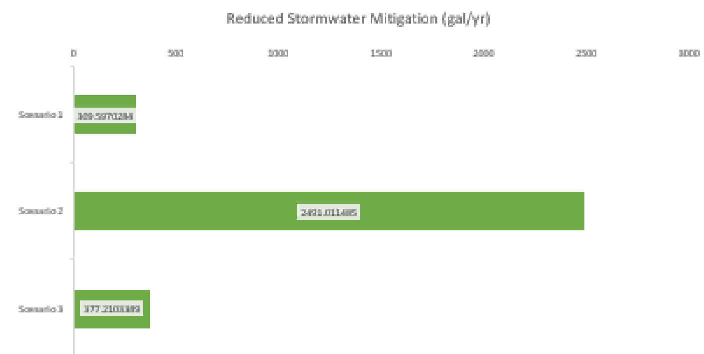




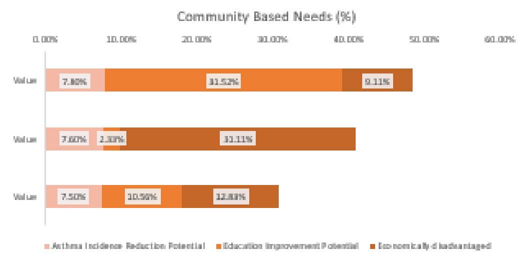
Environmental Co-Benefits

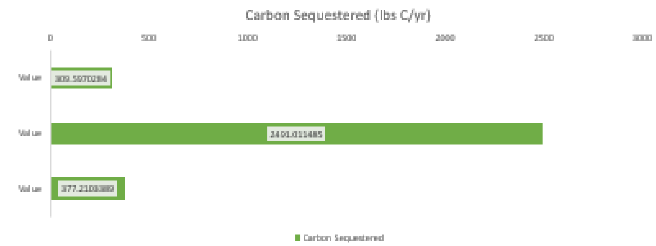




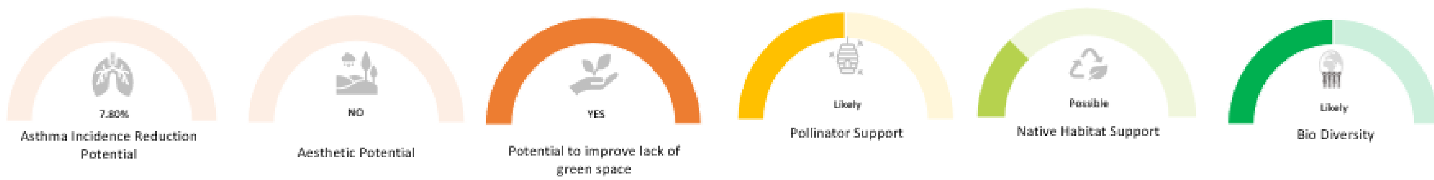


Social Co-Benefits

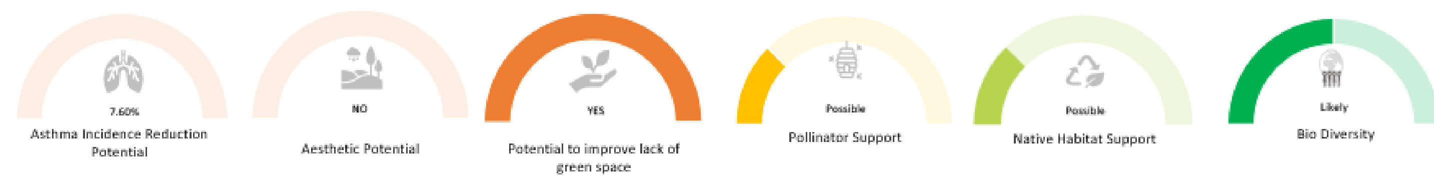




Scenario 1



Scenario 2



Scenario 3