DEPARTMENT OF TRANSPORTATION

Re-Use Of Minnesota Waste Material In Sustainably Design Soils Part 2

David Saftner, Principal Investigator
Civil, Environmental, and Geo- Engineering
University of Minnesota

September 2024

Research Project
Final Report 2024-23

LRRB
LOCAL
ROAD RESEARCH
BOARD

Technical Report Documentation Page

1. Report No. MN 2024-23	2.	3. Recipients Accession No.
4. Title and Subtitle Re-Use Of Minnesota Waste Material In Sustainably Design Soils. Part 2		5. Report Date September 2024
		6.
7. Author(s) David Saftner, Meijun Cai, Matt Aro, Godbless Amoateng		8. Performing Organization Report No.
9. Performing Organization Name and Address Department Of Civil Engineering University Of Minnesota Duluth 221 Swenson Civil Engineering 1405 University Drive Duluth, MN 55812		10. Project/Task/Work Unit No. # 2023013
		11. Contract (C) or Grant (G) No. (c) 1036342 (wo) 53
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Office of Research & Innovation 395 John Ireland Boulevard, MS 330 St. Paul, Minnesota 55155-1899		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code
15. Supplementary Notes http://mdl.mndot.gov/		

16. Abstract (Limit: 250 words)

Minerals, forestry, agriculture, and industrial activities in Minnesota generate substantial by-products and waste. Strategies to reuse or recycle these can reduce landfill waste, enhance public health, conserve resources, and cut costs and emissions. Building on the frameworks by Johnson et al. (2017), Saftner et al. (2019), and Saftner et al. (2022), this project extended its scope across Minnesota to include materials like dredge sediment from Mississippi River, RCA (recycled concrete aggregate) and VersaLime. Researchers identified, selected, and characterized various waste, by-products, and commercial materials statewide, as well as tested engineered soil mixes for roadway applications, assessing their stormwater retention and support for native plants. Laboratory methods characterized these mixes, which were implemented and evaluated *in situ*. A preliminary environmental life cycle assessment (LCA) was also conducted quantifying the environmental impacts of the engineered soil mixtures. Results were compiled into a design guide for the Minnesota Department of Transportation (MnDOT) engineers.

17. Document Analysis/Descriptors Waste products (Materials), Roads, Runoff, Soil tests		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 143	22. Price

Re-Use Of Minnesota Waste Material In Sustainably Design Soils—Part 2

Prepared by:

David Saftner
Godbless Kwame Amoateng
Department of Civil Engineering
University of Minnesota Duluth

Meijun Cai
Matt Aro
Natural Resources Research Institute
University Of Minnesota Duluth

Final Report

September 2024

Published by:

Minnesota Department of Transportation
Office of Research & Innovation
395 John Ireland Boulevard, MS 330
St. Paul, Minnesota 55155-1899

ACKNOWLEDGEMENTS

The research team is grateful for the funding provided by the Minnesota Department of Transportation (MnDOT) for this project. Special thanks are due to Dwayne Stenlund for his significant contribution serving as the Technical Liaison and Barbara Fraley for her significant contribution serving as the Project Coordinator. We also extend our appreciation to the members of the project's Technical Advisory Panel (TAP) for their invaluable guidance and expertise.

The research team thanks the following businesses and organizations for their valuable contributions to this study by supplying sample materials. We deeply appreciate their involvement and support.

- U.S. Army Corps of Engineers
- Northland Constructors
- American Crystal Sugar Company
- American Peat Technology
- Lester River Sawmill
- Sappi Global

Table of Contents

List of Figures

List of Tables

Executive Summary

This project aims to develop a statewide guide for designing resilient and sustainable engineered soil mixes that can reduce volume and pollutants, supporting native vegetation. This initiative builds on prior research by incorporating various waste materials and by-products sourced from industries across Minnesota, including peat/biochar blends, dredged sediments, pine and ash sawdust, VersaLime, lime mud, bottom ash, degritter and recycled concrete aggregate (RCA). These materials underwent extensive laboratory testing to evaluate their biological, environmental, and civil engineering properties. Based on laboratory testing results, five materials were chosen to create three distinct types of mixtures for field experimentation. These mixtures comprised dredge sediment (80%) with degritter (20%), RCA (80%) with ash sawdust (20%), and RCA (80%) with peat/biochar (20%). These soil blends were then used to establish field experiment plots within a parking lot for comprehensive field testing. Field monitoring data obtained from the newly established plots were subsequently compared with data from previously built field sites. These included seven additional experimental plots within the same parking lot and a site located by the roadside. This comparative analysis facilitated a thorough assessment of the performance and efficacy of the newly constructed plots relative to existing field conditions. Following these assessments, a specific engineered soil mix was formulated following Minnesota Department of Transportation (MnDOT) standards and subjected to further testing. A comprehensive life-cycle analysis was then conducted on both the individual materials and the final engineered mix to assess their sustainability and effectiveness.

CIVIL ENGINEERING

The primary design consideration in civil engineering for this project was the infiltration rate. To assess the worst-case scenario, saturated hydraulic conductivity was the key parameter used to evaluate materials and their combinations, building on findings from previous studies by Johnson et al. (2017) and Saftner et al. (2019, 2022). Laboratory tests on by-products revealed that hydraulic conductivity was determined by the finest material in the mix. Typically, organic materials exhibited high hydraulic conductivities, and generally, coarser materials demonstrated higher conductivities than finer ones. The hydraulic conductivity values of the engineered mixes were intermediate, influenced predominantly by the material with the lowest conductivity in the mix. From 2017 to 2024, monitoring of two field plots assessing the performance of the engineered mixes confirmed that the media effectively captured the first inch of excess precipitation directed toward the biofiltration system.

ENVIRONMENTAL ENGINEERING

The environmental assessment aimed to comprehensively characterize the chemical properties of various materials and assess the potential release and removal of pollutants, including metals, nitrogen, phosphates, and per- and polyfluoroalkyl substances (PFAS). Overall, the examined materials showed generally low levels of nutrients, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs), resulting in relatively low pollutant release. However, it was noted that the alkaline nature of lime mud and bottom ash, alongside the acidic nature of ash and pine sawdust, necessitates careful consideration during application. These materials should either be applied to land with complementary pH properties or mixed with other substances to neutralize their pH.

The study of PFAS release represents an initial exploration, given the absence of standardized leaching methods. Out of the 18 PFAS species studied, nine were detected in the leachate, with concentrations consistently below 1 µg/kg. Additionally, most materials exhibited strong capacities for removing metals and nutrients. Notably, bottom ash, peat/biochar mix, and RCA demonstrated high removal percentages for copper, lead, and zinc, while phosphate removal was particularly effective at high pH levels. For the field plots, stormwater runoff after filtration through these materials typically exhibited copper and zinc concentrations below 1,000 ppb and phosphate concentrations below 100 ppb, comparable with results from the previously constructed seven sites, which were built with compost, salvaged peat, or tailings. Throughout the seven-year monitoring period for these seven old experimental plots, clear declining trends in phosphate concentrations were observed, particularly evident at the compost site, where concentrations decreased from 5,000 ppb to around 700 ppb.

PLANT GROWTH ASSESSMENT

Plant growth was assessed through greenhouse testing using radish and oat seeds. The studied nine individual media and three mixed media formulations were evaluated over a 21-day period to track germination rates, plant heights, and biomass production. Notably, plants exhibited minimal growth in alkaline media such as bottom ash, lime mud, and VersaLime. The peat/biochar mix, while fine-grained, showed limited water filtration capacity, resulting in reduced plant growth rates. Conversely, the remaining five individual materials and three mixed media combinations supported robust plant growth in the greenhouse setting. However, in the field experiment plots, plant growth with the three mixed media formulations was negligible during the 2023 season, likely due to an extended dry spell in summer. Long-term monitoring will be essential to observe plant growth patterns in the field plots over time.

LIFE-CYCLE ASSESSMENT (LCA)

The preliminary LCA revealed that transportation contributed nearly 100% of the impacts in each impact category. A comparative analysis revealed that the dredge sediment (80%) with degritter (20%) engineered soil mix had substantially higher impacts than the RCA (80%) with ash sawdust (20%) and RCA (80%) with peat/biochar (20%) engineered soil mixes; it also had the largest CO_2 emissions to air. While the RCA (80%) with ash sawdust (20%) engineered soil mix had the lowest impacts in each category, it was very similar to those of the RCA (80%) with peat/biochar (20%) engineered soil mix. Differences between these two mixes varied from a low of 4.32% for human health to 4.55% for cumulative energy demand. Future research could consider how local or regional soil or similar materials perform regarding emissions of contaminants compared to the three engineered soil mixes studied, as well as costs for any required soil processing and transport to the installation site.

DESIGN GUIDE

The guide developed under this project promotes the use of locally sourced waste materials and by-products as substitutes for sand and/or compost while still adhering to regulatory standards. The recommended practices are designed to be standard, common, and repeatable, minimizing implementation barriers. Engineered soil mixtures offer benefits such as sustainable material reuse, reduced costs for sand and compost, lower transportation expenses, and diminished environmental impacts associated with material transport. This guide is a component of a MnDOT research project detailed in MnDOT Contract No. 1036342, Work Order No. 53, titled *Re-use of Minnesota Waste in Sustainably Designed Soils – Part 2*. The full report provides comprehensive details and background, and it is advised to reference this report when using the guide.

CHAPTER 1: INTRODUCTION

1.1 MOTIVATION

Minnesota produces numerous high-volume by-products and waste materials from the mineral, forestry, agricultural, and industrial sectors. Reusing or recycling these materials can conserve natural resources while reducing material costs. According to the Minnesota Pollution Control Agency (MPCA, 2013), nearly two-thirds of what ends up in landfills and garbage incinerators in Minnesota could have been reused, recycled, or composted. If the current trends continue, eight million tons of additional waste will be sent to landfills over the next 20 years. Reducing the amount of waste going to landfills will improve public health, conserve energy and natural resources, and reduce pollution and greenhouse gas emissions. The production of new products involves various processes that release greenhouse gases, contributing to the worsening of climate change. Furthermore, this production requires a significant amount of materials and energy that could lead to a further deterioration in environmental impacts (EPA, 2015). That is, raw materials must be extracted from the earth and the product must be fabricated and then transported to wherever it will be used. As a result, reduction and reuse are the most effective ways to save natural resources, protect the environment, and save money.

The initial surface runoff of a rainstorm, commonly referred to as "first flush," carries a substantial amount of pollutants such as suspended solids, metals, and organics. If left untreated, these pollutants can pose a serious threat to aquatic ecosystems and the organisms that inhabit them. Therefore, proper treatment of first-flush runoff is essential to prevent environmental harm. To minimize the impact of the polluted stormwater, the National Pollutant Discharge Elimination System (NPDES) State Disposal System (SDS) General Permit issues that, the first flush of stormwater runoff from new impervious surfaces should be held onsite through infiltration, harvesting, or reuse (MPCA, 2013). As seen in Figure 1.1, the biofiltration system such as bioslopes, bioswales, and vegetative cover strips could be used to reduce the level of contaminants from the first flush of runoff by absorption and plant uptake to meet the water-quality standards.

Figure 1.1 Biofiltration system along a highway in Montana (Flexamat, 2002)

Traditionally, stormwater management has involved the rapid conveyance of water via storm sewers to surface waters. Low-impact development (LID) techniques are gaining popularity for supplementing traditional best management practices and reducing infrastructure needs. LID measures route runoff from impervious surfaces to natural or constructed features where it can infiltrate the soil.

LID is a different approach that retains and infiltrates rainfall on-site. The LID approach emphasizes site design and planning techniques that mimic the natural infiltration-based, groundwater-driven hydrology of St. Louis County's historic landscape (Metropolitan St. Louis Sewer District, 2020). Bioswales and bioslopes are one component of LID. Protecting public health by reducing urban stormwater runoff (Figure 1.2) and associated nonpoint source pollution makes sense as a complement to water treatment infrastructure and health-care interventions (Gaffield et al, 2003).

This project aimed to identify, select, and characterize waste, by-products, and commercial materials available across Minnesota to create engineered soil mixes capable of meeting stormwater retention requirements and supporting native plant establishment. In addition to that, a design guide was created for Minnesota Department of Transportation (MnDOT) engineers to use in stormwater management applications, primarily bioslopes and bioswales, but also in related applications such as topsoil supplements. Johnson et al. (2017) and Saftner et al. (2019) provided a framework for this project using materials from Northeast Minnesota.

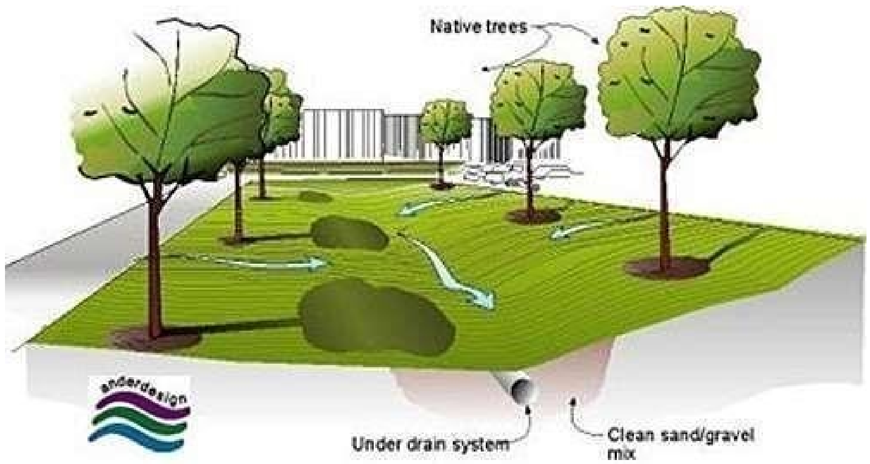

Figure 1.2 Low Impact Development Technology (WBDG 2016)

1.2 OUTLINE

This project aims to identify, select, and characterize waste materials, by-products, and commercial materials available across Minnesota to create engineered soil mixes capable of meeting stormwater retention requirements and supporting native plant growth. Chapter 2 presents a literature review on the application of waste materials in stormwater management BMPs. Chapter 3 describes the methods that will be used to quantify the civil engineering, environmental engineering, and biological properties of the waste materials in the laboratory, along with the results from *in-situ* tests. The material collection is discussed in Chapter 4. The experiment results created using the methods described in Chapter 3 are presented and discussed in Chapter 5 while the field monitoring results are reported in Chapter 6. Chapter 7 gives a life-cycle assessment, primarily focusing on the environmental impacts. Then Chapter 8 comprises a designed guide for Minnesota state engineers, while Chapter 9 presents the conclusions of the study.

CHAPTER 2: LITERATURE REVIEW

2.1 BACKGROUND

Stormwater runoff refers to the rainfall that flows over the ground surface. It is created when rain falls on roads, driveways, parking lots, rooftops, and other paved surfaces that do not allow water to soak into the ground. Stormwater runoff is the number one cause of stream impairment in urban areas (CWP, 2020). Where rain falls on paved surfaces, a much greater amount of runoff is generated compared to runoff from the same storm falling over a natural area. These large volumes of water are swiftly carried to streams, lakes, wetlands, and rivers.

As stormwater runoff flows over these surfaces, the water picks up dirt, dust, rubber, and metal deposits from tire wear, antifreeze, etc., that have accumulated on the pavement, as well as chemicals, bacteria, and other litter (EPA,1995). However, stormwater design and "green infrastructure" capture and reuse stormwater to maintain or restore natural hydrology. Detaining stormwater and removing pollutants is the primary purpose of stormwater management (EEC, 2018). The MPCA under the NPDES / SDS enforces a permit to discharge stormwater. The requirements set out in this permit state that the stormwater retention system "must provide a live storage volume of one inch times all the impervious area draining to the basin" (MPCA, 2013). If the area of the infiltration systems typically is the same size as the impervious area that is draining towards the system, then the system needs to be able to capture the first one inch of rainfall per rainfall event. Biofiltration system is one of the approaches that is widely used to help solve this problem.

2.2 BIOFILTRATION SYSTEM

Biofiltration refers to the simultaneous processes of filtration, infiltration, adsorption, and biological uptake of pollutants in stormwater that take place when runoff flows over and through vegetated treatment facilities (WA Department of Ecology, 1992). Its design options may include vegetative filter strips, bioswales, bioslopes, wet ponds, detention ponds, treatment wetlands, or combinations of these as seen in Figure 2.1.

One of the design principles that the MPCA has for stormwater management systems is that each system mimics pre-development hydrology. The practice should operate in a manner to replicate pre-development hydrology for a range of storm events such that it safely recharges groundwater, protects downstream channels, and reduces off-site flood damage (MPCA, 2021).

Figure 2.1. Biofiltration system with vegetated foreslope, backslope, and swale (Mitchell et al., 2010).

MnDOT and local agencies control stormwater runoff from roadways through a range of settlement, filtration, and infiltration facilities, such as wet ponds, infiltration basins, trenches, and swales. Infiltration facilities have been used for more than 30 years, but a high rate of failure has been tied to inaccurate determination of soil infiltration rates. To meet state regulations that prevent excess rain and road contaminants from entering the watershed, MnDOT and other agencies construct various kinds of stormwater management devices, including low-impact development installations such as bioslopes and bioswales that mimic the natural landscape. Engineered bioslopes and bioswales are built along some roadways during highway construction. As seen in Figure 2.2, they contain filter materials that have been amended, typically mixtures of compost and sand that enhance the slope's capacity to contain and filter rainwater, as well as support plant growth (MnDOT, 2015).

2.2.1 Bioslope

Bioslopes are flow-through water quality facilities incorporated into roadside embankments.
They are located between the edge of the pavement and a downstream conveyance system. Bioslopes use a variety of physical, biological, and chemical treatment processes to provide stormwater treatment. Bioslopes are often used in conjunction with water-quality filter strips. Bioslopes (Figures 2.3 and 2.4) are recommended for highway applications because of their minimal right-of-way requirements and minimal maintenance requirements. Synonyms for bioslopes include ecology embankments and media filter drains (SOM Manual, 2018).

Figure 2.2. Biofiltration Design (Greendale Grange Ave Bioswale, 2010)

Figure 2.3. Bioslope at Crow Wing County, Minnesota Stormwater Manual (2018)

Bioslopes are designed with limited longitudinal slopes to force the flow to be slow and uniform, thus allowing particulates to settle and limiting the effects of erosion. Larger flow rates from high-intensity storm events in the form of sheet flow bypass the engineered soil media by overtopping and continuing down the embankment or slope (Augusta Stormwater Management Manual, 2022).

Figure 2.4. Bioslope along Roadside (Georgia Stormwater Manual)

2.2.2 Filter Strips

Filter strips are flow-through water quality facilities located along the right-of-way parallel to the road. They are designed to treat sheet flow from adjacent impervious surfaces and consist of a flat cross slope to maintain sheet flow over the entire width of the strip. Treatment occurs as the stormwater runoff flows through the grass and soil surface (Figure 2.5). Vegetation, such as grasses and native plantings, are used in temperate climates. In arid areas, aggregate media may be used instead of vegetation if the underlying soil supports infiltration (SOM Manual, 2018). The underlying soil can be amended to create an approved water quality mix if the existing soil does not meet infiltration standards.

Figure 2.5. Grass filter strip draining to vegetated swale (Trinkhaus Engineering, 2018)

Filter strips tend to be rectangular in design and consist of the right-of-way parallel to the road with a flat cross slope to maintain sheet flow of stormwater runoff over the entire width of the strip (Figure 2.6). Filter strips are recommended for highway application because of their minimal maintenance requirements (SOM Manual, 2018).

Figure 2.6. Vegetated filter strip (Trinkhaus Engineering, 2018)

2.2.3 Bioswales

A bioswale is a landscape element that is designed to capture and filter contaminants and sediments from stormwater runoff. Bioswales provide effective treatment of stormwater runoff without the extensive maintenance required for some other stormwater BMPs. Pollutant removal rates increase when bioswales are well maintained and as the residence time of water in a swale increases. The effectiveness of bioswales is also dependent upon the retention time of the stormwater in the bioswale. With a longer retention time, the removal efficiency is higher (Jurries, 2003).

Bioswales can also be differentiated into dry or wet swales based on treatment conditions at the site (Figure 2.7). A dry swale is a traditional bioswale whereas a wet bioswale is used in situations where the bed soil will tend to be saturated based on flow conditions, a high groundwater table, or seeps (WSDOT, 2014).

Figure 2.7. Bioswale adjacent to a roadside (Iowa stormwater management, 2017)

Bioswales, shown in Figure 2.8, can remove and immobilize or break down a large portion of pollutants found in stormwater runoff. Bioswales have achieved high levels of removal of total suspended solids (TSS), turbidity, and oil and grease. They can also remove a moderate percentage of metals and nutrients in runoff. This lower level of removal compared to sediment or oil and grease is due partly to the large percentage of metals and nutrients that appear in dissolved form in the runoff. The term "dissolved form" includes microscopic particulate that generally is referred to as turbidity (Jurries, 2003)

Figure 2.8. Bioswale (Iowa stormwater management, 2017)

2.3 BY-PRODUCTS USE AS FILTRATION MEDIA

Presently, MnDOT uses compost as soil amendments to *in-situ* soils for bioslope and bioswale construction. Saftner et al. (2017, 2019) conducted a series of research by determining the characteristics of various naturally occurring water-absorbing and filtering materials such as peat, muck, etc. In-situ testing was done on existing biofiltration systems to find out the various characteristics and the results were compared to laboratory testing. This research addressed concerns about transportation and purchasing costs for clean granular and compost, as well as nutrient leaching especially when compost is used as a soil amendment (Johnson et al., 2019).

Saftner et al. (2019, 2022) explored the potential reuse of waste materials from Northern Minnesota as a soil amendment in catching the first flush from the newly constructed impervious area. They also monitored soil moisture changes, infiltration water quality, and the absorption of phosphorus and other metals by the biofiltration system at different study areas.

This research does not only aim to provide an alternative to compost as a soil amendment using by-product materials at a statewide level but also to develop a guide for engineers in Minnesota to facilitate the implementation of research findings. The alternate by-products must meet the requirements specified in the Minnesota Standard Specifications 2018 for filter topsoil borrowing. MnDOT 3877.2G defines filter topsoil borrowing as consisting of 60%-80% sand that meets the gradation requirements of MnDOT 3126 (Table 2.1), and 20%-40% Grade 2 compost per MnDOT 3890-2 (Table 2.2, MnDOT, 2018) as shown in Figure 2.8. While the primary focus of this research is for application in stormwater management, the lessons learned apply equally well to related applications, including stormwater slope interception and topsoil suppliments.

Table 2.1. Fine Aggregate Gradation Requirement (MnDOT, 2018).

Fine Aggregate Gradation Requirements	
Sieve Size	Percent Passing
3/8 in	100
No. 4	95-100
No. 8	80-100
No. 16	55-85
No. 30	30-60
No. 50	5-30
No. 100	0-10
No. 200	0-2.5
*Percent passing by weight through square opening sieves	

Table 2.2. Grade 2 compost requirements (MnDOT 2018)

	Grade 2 Compost Requirements
Requirement	Range
Organic matter content (dry weight)	≥ 30%
C/N ratio	6:1 -20:1
NPK ratios (Max. %dry weight)	1:1:1
pH	5.5- 8.5
Moisture content	35%- 55%
Bulk density	700 lb. per cubic yard- 1600 lb. per cubic yard
Inert material *	< 3% at 0.15 in
Soluble salts	≤ 10 mmho per cm
Germination test ‖	80% - 100%
Screened particle size	≤ ¾ in
*Includes plastic bag shreds ‖Germination test must list the species of Cress, cucumber, or lettuce seed used.	

CHAPTER 3: MATERIALS AND METHODS

3.1 POTENTIAL MATERIALS

3.1.1 Mulch

In ecological horticulture, mulch refers to organic matter such as leaves or grass cuttings that are applied to protect and supply the soil with nutrients. Mulch products include natural materials such as straw and other grasses, coconut fiber, and bark. Synthetic mulches combine a variety of chemical bonding agents with wood fibers, cellulose, or synthetic fibers (bonded fiber matrix). Mulch products, shown in Figure 3.1, are intended to reduce raindrop splash erosion, decrease sheet erosion, promote infiltration, increase soil moisture retention, regulate soil temperature, and, in most cases, improve soil texture and increase organic matter. The choice of materials and anchoring of mulches should be based on slope steepness and length, soil conditions, season, type of vegetation, and size of the area (MPCA, 2019).

Figure 3.1. Nature Blend Mulch from Zimmerman Mulch

Mulches are applied to the soil surface to conserve desirable soil properties and promote plant growth. Mulching can be an effective means of controlling runoff and erosion on disturbed land. Mulches increase the infiltration rate of the soil, reduce soil moisture loss by evaporation, prevent crusting and sealing of the soil surface, control soil temperatures, and provide a suitable microclimate for seed germination. Organic mulch materials such as straw and hay are the most effective, followed by wood chips, bark, and fiber (MDT, 2015).

3.1.2 Expanded Shale

Shales are the most common sedimentary rocks. It is a fine-grained rock and often has a thinly laminated structure. Their color is commonly sometimes gray although they may be white, yellow, brown, red, or green to black. They are mainly composed of clay minerals with occasionally quartz and mica. Clay is the major constituent of shale. As clay is compacted by pressure, over geologic time it becomes shale. When the shale is crushed and fired in a rotary kiln at 2000°F, it causes the tiny air spaces in the shale to expand. The resulting process is called˚expanded shale or vitrified shale as seen in Figure 3.2.

According to Nature's Way Resources, expanded shale has good insulating properties, increases soil porosity, and absorbs 38% of its weight in water. It conservatively lasts for years (decades) in the soil and does not change pH. Expanded shale improves drainage and aeration (retains 30% of air space). It is non-toxic, odorless, 100% inert, and inorganic so it does not decompose. Expanded shale does not react with chemicals and is lightweight and easy to handle. The final benefits include being economical and readily available.

As a result, it now is used in higher quality soil mixes for containers as over-watering causes more plant death than any other cause. Expanded shale can be used to lighten heavy clay soil. It has also been incorporated into lightweight aggregates that are mixed into concrete instead of heavy sand or gravel and used in construction. It has been used in the designs for rooftop gardens and green roofs, which allow plant life to be supported at half the weight of soil. Expanded shale has been in aquaponic and hydroponic systems, as it has a large amount of surface area for beneficial bacteria. It is used in all forms of structural soils, as backfill and drainage material, and biofilter in water gardens and retention ponds (Grant, 2021).

Figure 3.2. Fractured Shale Stone from the shores of Cobscook Bay Pembroke, ME

It is also used as a filter material and in potting mixes as it does not deteriorate like vermiculite or decompose like peat moss. When used in a soil mix, it has been shown that plants have increased roots and root development, increasing plant growth and health.

3.1.3 Granite Waste

Granite waste is industrial waste produced from granite crushing in the industry of granite polishing. It has similar properties to pozzolanic materials such as fly ash and silica fumes. The waste of granite is produced through several processes. Cutting and polishing the blocks of granite produces a powder that is executed with water. When the water is evaporated, the remaining sludge of granite is carried and discarded (Ahmed et al, 2021).

Granite dust contains many nutrients and minerals that can be easily absorbed by plants. This soil amendment improves plant structure and increases resistance to pests and diseases (Kietzer et al., 2017).

Figure 3.3. Granite waste from the stone processing shop

Granite dust is a non-plastic material hence, adding granite dust, shown in Figure 3.3, to plastic soils reduces the plasticity index by breaking the particle–water–particle bond and the liquid and plastic limits. Adding granite dust to soil increases the maximum dry density (MDD) and reduces the optimum moisture content (OMC) due to the increase in coarser fraction and the specific gravity of soil–granite dust mixes (Nwaiwu et al., 2012). The unconfined compressive strength of clay is improved with the addition of granite dust content up to 20% and decreased with a further increase in granite dust addition. The coefficient of permeability of clay proportionally increased with the addition of granite dust (Nayak et al, 2011).

When granite weathers, it undergoes a process of disintegration and breaks down into smaller particles. This weathering can release minerals and elements into the surrounding soil, potentially affecting its pH level. Therefore, while granite weathering may have some influence on soil pH, it is unlikely to significantly alter the overall acidity or alkalinity of a larger area of soil.

In summary, granite dust enhances the geotechnical properties of silts and clays. High-plastic clays and clayey soils hold poor gradation; thus, the granite dust addition turns the mix into a well-graded complex.

3.1.4 Recycled Concrete Aggregate

Recycled concrete aggregates (RCA) also called crushed concretes are made up of asphalt debris from construction projects that can be reused to create driveways, pathways, garden beds, and more. When any concrete structure, road, sidewalk, or parking lot is destroyed, that concrete is often deposited in a landfill. Concrete that is not biodegradable will not decompose. Rather, RCA, as seen in Figure 3.4, can be reused to help reduce landfill crowding and save more resources from being used to create new concrete. Old concrete can be crushed to specific sizes, cleaned so that unwanted debris is removed from the mixture, and reused as a solution to several construction and landscaping problems.

Figure 3.4. Recycled Concrete Aggregate from a construction project.

Smaller, more broken-up concrete is a great drainage option for gravel. Adding RCA to build a soil layer will lighten the texture, allow better drainage and aeration, and discourage compacting soil. These factors are all essential to enable plants to grow (Superior Groundwater, 2020). According to Engelsen et al. (2010) and Gupta et al. (2018), RCA leachate pH values range from 10.6 to 12.8 when measured at a liquid-to-solid ratio (L/S) of 10, indicating that RCA can have an alkaline effect on soil pH.

3.1.5 Rock Tailings

Rock tailings are the waste material that remains after processing ore, ore concentrate, or mined materials. This waste material could include ground rock material, sand, clay, process chemicals or residual metals, minerals or bitumen, and sulfur. The accumulation of some tailings in tailings ponds can pollute groundwater and the surrounding environment (Pedro et al., 2019; Liu et al., 2020).

Figure 3.5. Tailings and waste rock samples, Eurofins.

Iron ore tailings (IOT) as seen in Figures 3.5 and 3.6 are a form of solid waste produced from processing iron ore. Among all kinds of mining solid waste, IOTs are one of the most common solid wastes in the world due to their high output and low utilization ratio (Tang et al, 2019). Iron ore tailings have been proven to improve the mechanical properties of expansive soil (Chethan et al., 2022).

3.1.6 Wood Chips

Wood chips, shown in Figure 3.7, are small- to medium-sized pieces of wood formed by cutting or chipping larger pieces of wood such as trees, branches, logging residues, stumps, roots, and wood waste. As they break down, they slowly provide some amount of nutrients and increase the pH and the organic matter in the soil. This organic matter helps to improve soil moisture, reduce erosion and compaction, and maintain the optimal temperature of the soil (Watson et al., 2014).
The increased organic matter in the soil results in healthier plant growth.

Figure 3.6. Iron ore tailings in Duluth.

Figure 3.7. Wood Chips piled up on the farm.

3.1.7 Dredge Sediments

Dredged sediment can be very valuable for agricultural improvement as the finer fractions can contain high levels of organic matter, nitrogen, and sulfur with useful levels of phosphorus, potassium, and magnesium. One beneficial use of dredged sediments is to amend soils, especially farm soils. Dredged sediments can improve soil health by adding organic matter and nutrients, lowering bulk density, and slightly increasing soil pH (Daniels et al., 2007). Dredged sediments, shown in Figure 3.8, can contain organic matter in the form of lignin oligomers, marine and terrestrial humic acids, chlorophylls, carbohydrates, and other compounds (Ninnes, et al., 2017). Soil organic matter has a high surface area, provides energy to soil microorganisms, and provides nutrients for plants (Lal, 2006, 2016).

Figure 3.8. Dredge sediments from Lake Erie Ports.

Soil organic matter also contains carboxyl, hydroxyl, and phenol functional groups that mediate soil organic matter binding and stabilizing onto clay minerals (Arias et al., 2005). Amending farm soils with dredged sediments that are rich in organic matter can increase the soil cation exchange capacity and slightly increase the pH of the soil (Darmody & Ruiz Diaz, 2017). The U.S. Army Corps of Engineers (USACE) is responsible for maintaining various navigation projects in Minnesota, including Erie Pier in Duluth, and the Upper Mississippi River (UMR). The dredged sediment of the Erie Pier was investigated in the last phase of the project and was identified as a good material for soil amendment (Saftner et al., 2022). In this project, dredged sediment from the Mississippi River was collected from the Wabasha Gravel Pit. This gravel pit currently holds approximately 4,309,000 cubic yards of dredged material from four hydraulic transfers from the Reads Landing temporary site between 1985 and 2011 (internal communication). From the visual examination, this material primarily consists of sand, as shown in Figure 3.9, which is significantly different from the dredged sediment from Erie Pier. Currently, this material is being used for construction, but the consumption amount accounted for a small proportion of the existing material.

Figure 3.9. The site picture of the dredged sediment in the Wabasha Gravel Pit.

3.1.8 Wood Ash

Wood ash is the powdery residue remaining after the combustion of wood. It is largely composed of calcium compounds, phosphorus, magnesium, and sulfur along with other non-combustible trace elements (manganese, iron, aluminum, zinc, boron) present in the wood. These nutrients are beneficial for plant growth. Figures 3.9 and 3.10 show examples of a wood ash application project in Minnesota.

Figure 3.10. Wood ash after burning of wood.

In addition to its nutrient content, wood ash can help in neutralizing soil acidity. When wood is burned, high amounts of carbonates are produced. Carbonates react with and neutralize the acid in the soil, causing the soil pH to increase.

Figure 3.11. Shows the difference in plant growth using wood ash in Minnesota.

3.1.9 Waste Materials From Paper Mill

Waste reduction is one of the major sustainability initiatives for many industries, including paper mills. Common waste materials include bottom ash from the burner, wood or recycled paper fibers, lime mud from chemical processes, and sludge. Most of these waste materials are typically sent to landfills or incinerated. However, some of them possess potential for reuse. For instance, bottom ash exhibits metal adsorption capabilities, while lime mud can be utilized to elevate soil pH due to its alkaline properties. By exploring such reuse opportunities, industries can contribute to waste reduction and promote environmental sustainability.

3.1.10 Waste Peat And Biochar Mix

American Peat Technology (APT) is a research company that specializes in providing peat-based products to remove pollutants. The material is a waste stream from their baghouse. During the manufacturing process of peat/biochar microbial carrier, the dryer emissions are routed through a baghouse. The material accumulated in the bag is regularly removed. Typically, the waste is composed of approximately 40% of peat and 60% of biochar. As both peat and biochar demonstrate unique properties in pollutant removal, this material probably can enhance stormwater treatment when it is mixed with soil.

3.2 METHODS

3.2.1 Introduction

This section provides an outline and a brief description of the methods and techniques that were used to categorize and evaluate the properties of filter materials utilized in biofiltration systems for stormwater management. Waste materials that were tested include bottom ash, degritter, lime mud, dredged sediments, recycled concrete aggregate, sawdust, beet tailings, versa line, iron ore tailings, granite waste, and mulch. Initially, individual materials went through laboratory testing to ascertain their compliance with the civil and environmental engineering criteria. Subsequently, material blends were produced. The effectiveness of newly developed filter media blends was assessed by comparing their performance to that of compost-based media mixtures already in use, which are defined by the 2016 MnDOT General Construction Specifications Section 3877.2(G) under the label "Filter Topsoil Borrow as seen in Tables 2.1 and 2.2.

3.2.2 Laboratory Tests

3.2.2.1 Gradation Test

The gradation test was performed to determine the percentage of each grain size that was contained within the study material and the engineered mixes if they met the MnDOT specifications, and the results of the test was used to produce the grain size distribution curve. This information helped classify the materials and to predict their behavior. The methods are described below:

SIEVE ANALYSIS

Sieve analysis was carried out to determine the particle size distribution of a sample of material according to ASTM D6913-04. The procedure involved placing a representative sample of the material to be analyzed on a series of sieves with progressively smaller openings, starting with the largest sieve at the top and ending with the smallest sieve at the bottom. The sieves were then mechanically shaken for a specified amount of time, typically 10 to 15 minutes, to ensure that all particles were separated into their respective size fractions. Once the shaking is complete, the amount of material retained on each sieve is weighed, and the cumulative weight percentages of the material passing through each sieve are calculated.

HYDROMETER

The hydrometer test was performed on fine-grained soils, such as silts and clays, according to ASTM D7928-21e1. The hydrometer test involved mixing a representative soil sample with water to create a suspension, which was then allowed to settle for a specified amount of time. A hydrometer is then inserted into the suspension and the hydrometer reading is taken. The particle size distribution is calculated using a standard formula that considers the density of the soil particles, the density of the water, and the viscosity of the suspension.

ATTERBERG LIMITS

Atterberg limit tests were conducted on fine-grained soils to measure the soil's consistency, which is an important factor in determining its suitability for engineering purposes. The ASTM standard D4318 is a used method for conducting Atterberg limit tests specifically the Liquid limit test and Plastic limit test.

The liquid limit test was performed on soils that have passed through sieve #40. Distilled water is added to this soil fraction until it has a consistency of peanut butter or frost. A portion of this soil is placed in a liquid limit device and a grooving tool is used to make a groove in the soil. The crank on the liquid limit device is turned at a rate of two cranks per second and the groove is closely observed. A portion of the soil is taken once the groove closes and its water content is obtained by using ASTM D2216.

The plastic limit test was done by rolling a mixture of soil that passed through sieve #40 and water to form a rod with a diameter of 0.125 inches. Rolling of soil is done until it crumbles while making the rod. At this point, the water content of the soil is the plastic limit, and it is obtained by using ASTM D2216.

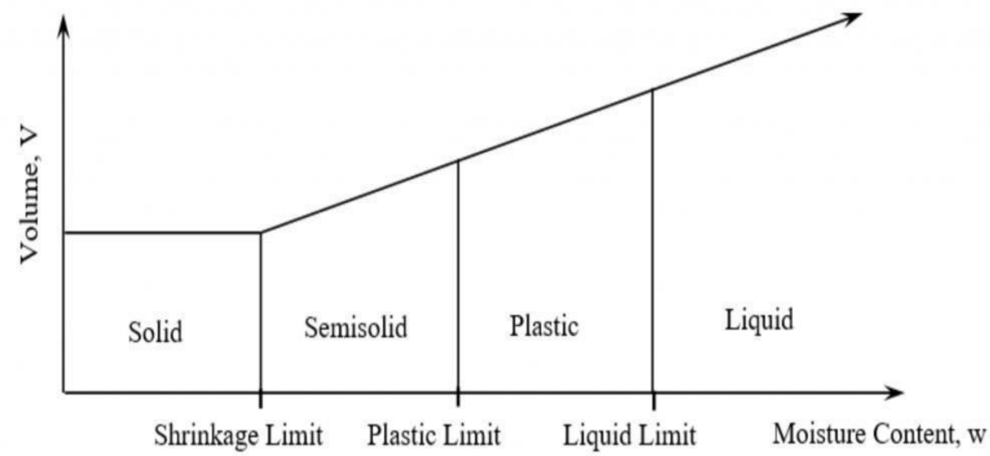

Figure 3.12. Qualitative positions of Atterberg limits on a moisture content scale.

3.2.2.2 Moisture Content

The moisture content test was performed to determine the amount of moisture in a soil sample according to ASTM standard D2216-19.

The moisture content test involved taking a soil sample and weighing it. The sample was then dried in an oven at a specified temperature for a specified time until it reached a constant weight. The sample was then re-weighed, and the difference between the two weights was used to calculate the moisture content of the sample.

3.2.2.3 Proctor Test

The Proctor compaction test was used to determine the maximum dry density and optimum moisture content of a soil sample and it was carried out by using ASTM D698-12**.** The Proctor test involved compacting a soil sample into a cylindrical mold using a controlled number of blows from a standard hammer of a specified weight and drop height. The moisture content of the soil sample was adjusted for each compaction test, and the dry density of the compacted specimen was measured. A series of compaction tests were performed at different moisture contents to determine the maximum dry density and optimum moisture content of the soil.

3.2.2.4 Hydraulic Conductivity Test

The hydraulic conductivity test was performed on both coarse-grained and fine-grained aggregate by using the constant head method and falling head method respectively. This test helped determine the rate at which water flowed through the soil sample under a specific condition. The ASTM standard that was used for the hydraulic conductivity test for coarse-grained material is ASTM 2434. The falling head method (Germaine & Germaine, 2009) was used to find the hydraulic conductivity of materials that behave like clay or silt. The hydraulic conductivity test involved saturating a soil sample with water and applying a pressure gradient to the sample to induce water flow. The rate of water flow was measured over a specified period, and the hydraulic conductivity of the soil was calculated using Darcy's law, which relates the rate of water flow to the hydraulic gradient and the properties of the soil. This project prepared the samples at 85% relative compaction (RC) to best mimic *in situ* conditions.

3.2.2.5 Strength Test

DIRECT SHEAR TEST

The direct shear test is a laboratory method used to measure the shear strength of soil specimens. The test was performed according to ASTM D3080-04. It involved placing a soil specimen between two horizontal metal plates and applying normal stress to the specimen while shearing it along a predetermined plane. The shear stress required to cause the failure of the specimen is measured, and the shear strength of the soil is calculated as the ratio of shear stress to normal stress.

3.2.3 Chemical Characterization

The chemical compositions of the studied materials were characterized to determine the contents of pH, organic matter, nutrients, and some major metals (copper, lead, and zinc). These compositions were important to determine if the media are suitable for plant growth. The characterization is conducted by the University of Minnesota Soil Testing Laboratory (https://soiltest.cfans.umn.edu/).

3.2.3.1 Chemical Release And Adsorption

Lab batch tests were conducted to evaluate the potential release or adsorption of chemicals when the media was mixed with synthesized stormwater. The major pollutants to be examined include nitrate, phosphate, copper, lead, zinc, and PFAS. Because the concentrations of PFAS are significantly lower than other chemicals, the batch tests were performed in two separate sets.

3.2.3.2 Nutrients And Metals

The synthesized stormwater was prepared by dissolving $NaNO_3$, Na_2HPO_4, $CuSO_4$, $PbCl_2$, and $ZnCl_2$ into milli-Q water (purified water which has been deionized/demineralized) into 3 liters. The amounts of each chemical used to prepare 3-L stock solution were: $NaNO_3$- 0.987g, $NaH2PO_4$ - 0.631g, CuCl2.2H2O, - 0.201g, $Pb(NO3)_2$,- 0.08g and $ZnCl_2$ – 0.209 g. The stock solution was diluted to get five concentration levels (Table 3.1).

For synthesized stormwater at each concentration level, 2.5 g of dry material (105oC for 24 hrs) was mixed with 250 ml of stormwater, as shown in Figure 3.12. The mixture was shaken on a shaking table at 100 rpm for 24 hours. After that, the mixture was filtered through a 0.45 µm filter membrane. The filtered water was collected and separated into two bottles. One bottle was stored in the fridge at 4^oC

for anion measurement by ion chromatography and another bottle was acidified by nitrate to pH<2 and stored at room temperature for metal measurement by atomic absorption spectroscopy. For each mixture, three replicates were included.

Table 3.1. The designed concentrations of chemicals in the synthesized stormwater.

Batch ID	NO3, mg/L	PO4, mg/L	Cu, µg/L	Pb, µg/L	Zn, µg/L
1*	0	0	0	0	0
2	0.375	0.25	37.5	25	50
3	1.5	1	150	100	200
4**	7.5	5	750	500	1,000
5	15	10	1,500	1,000	2,000
6***	75	50	7,500	5,000	10,000

*DI water, to test soluble chemical properties of filter media

**Minnesota maximum concentrations

***National maximum concentrations

Figure 3.13. The picture of the batch testing apparatus, including the shaking table, vacuum pump, and filtration funnel.

3.2.3.4 PFAS

The per- and polyfluoroalkyl substances (PFAS) are known as 'forever chemicals' as they are extremely persistent in our environment and bodies. As this group of chemicals has more than 9,000 compounds, we are particularly interested in the six compositions proposed by EPA for the National Primary Drinking Water Regulation (https://www.epa.gov/sdwa/andpolyfluoroalkylsubstances-pfas). These six compositions include perfluorooctanoic acid (PFOA), perfluorooctane sulfonic acid (PFOS), perfluorononanoic acid (PFNA), hexafluoropropylene oxide dimer acid (HFPO-DA, commonly known as GenX Chemicals), perfluorohexane sulfonic acid (PFHxS), and perfluorobutane sulfonic acid (PFBS). In addition, the Minnesota Department of Health (MDH) set the guidance values for PFBS, perfluorobutyrate (PFBA), PFHxS, perfluorohexanoate (PFHxA), PFOA, and PFOS (Table 3.2). In addition to the established standards for drinking water, EPA took significant action in April 2024 by designating PFOA and PFOS as hazardous substances under the Comprehensive Environmental Response, Compensation, and Liability Act. These compositions were examined in the leaching tests.

Table 3.2. The guidance values of several PFAs compositions by MDH

Chemical	Lowest EPA Health Advisory (µg/L)	Type of HA value	Lowest MDH Value (µg/L)	Type and date of MDH value	Duration of Exposure
PFBS	2	life-time	7	HRL11	Chronic
PFBS	2	lifetime	0.1	HBV22	Short-term
PFBA			7	HRL18	Short-term
PFHxS			0.047	HBV20	Short-term
PFHxA	0.07		0.2	HBV21	Short-term
PFOA and salts	0.07	lifetime	0.035	HRL18	Short-term
PFOS and salts	0.07	lifetime	0.3	HRL09	Chronic
PFOS and salts		lifetime	0.015	HBV20	Short-term

Abbreviations: HBV- MDH Health-Based Value; HRL - MDH Health Risk Limit.

PFAS leaching test was performed by mixing 750 ml HPLC water (the super clean water) with 75 g waste material in a 1000 ml bottle. The mixture was shaken at 150 rpm for three days to represent the typical wet duration after a major rainfall. After that, the mixture was centrifuged to separate the solid and the solution. The decanted solution was concentrated 500 times to elevate the PFAS concentrations to be measured by LC/MS.

3.3 PLANT GROWTH

Greenhouse trials were conducted to determine the ability of the individual materials and the mixture of selected waste materials to support plant growth. This test consisted of seed germination and plant growth tests for both radishes and oats in the NRRI greenhouse. The trials were performed in 21-day runs. One liter of the studied material was placed in 7” x 5” x 2” containers and placed in the greenhouse under constant temperature (68°F-75°F) and watered for 10 minutes daily by an automatic sprinkler watering system. For each media/mixture, six replications were planted with six oat seeds or six radish seeds for each replicate.

Germination/survival was recorded after seven days. After 21 days, the plant heights were measured, and the plants were harvested. The harvested plants were dried at 105°C for 48 hours to determine the plant biomass (shoots and roots) dry weights.

3.4 IN-SITU TESTING

Field experimental plots with selected media were constructed in the NRRI parking lot to determine the infiltration capacity, pollutant removal, and vegetative support capabilities of the media mixture. The mixture was composed of 20% organic and 80% inorganic. Six square media beds approximately 36 inches x 36 inches in size (two replicates for each mixture, Fig. 3.13) were prepared by placing six inches of treatment media over four inches of gravel. The gravel layer was included to promote drainage via an underdrain to the collection jug, which allowed for the determination of water quality effects. Grass and wildflower seed mix with a straw mulch cover was applied immediately after the construction. In addition, instrumentation that monitors rainfall, soil moisture content, temperature, and overland runoff (as described in the following section) was installed for in-situ field monitoring.

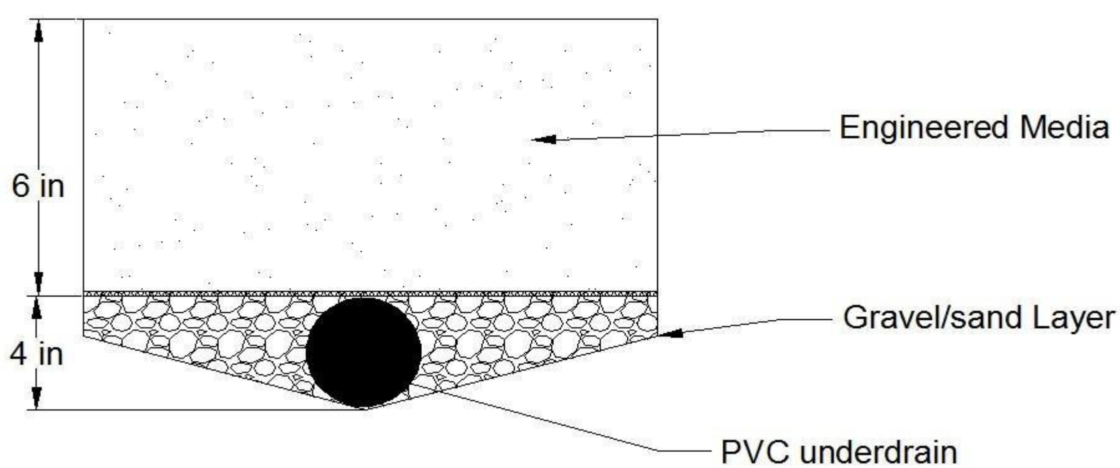

Figure 3.14. Cross section of mixed media pilot plant.

CHAPTER 4: MATERIAL COLLECTION

4.1 INTRODUCTION

The project will not incorporate all the materials discussed in Chapter 3, primarily due to the reasons shown in Table 4.1. Consequently, the selection of materials shown in Table 4.2 was used. Figure 4.1 shows a GIS map that has been created to visually represent the distribution of these materials across the state of Minnesota.

Table 4.1. Summary of materials that were not used in the project.

Material	Type	Reason
Wood Ash	Organic	Not accessible
Wood Chips	Organic	Too large for practical application
Rock Tailings	Inorganic	Studied in previous research
Granite Waste	Inorganic	Not accessible
Expanded Shale	Inorganic	Not accessible
Mulch	Organic	Not a waste material

Table 4.2. Summary of material, company, and location.

Material	Material Type	Company	Location
Bottom ash	Inorganic	Sappi	Cloquet
Degritter	Organic	Sappi	Cloquet
Lime mud	Inorganic	Sappi	Cloquet
Dredge sediment	Inorganic	U.S. Army Corps of Engineers	Wabasha
Recycled concrete aggregate	Inorganic	Northland Contractors	Duluth
Green pine sawdust and ash sawdust	Organic	Lester River Sawmill	Duluth
Beet tailings	Organic	American Crystal Sugar Co.	Crookston
VersaLime	Organic	American Crystal Sugar Co.	Crookston
Peat/biochar mix	Organic	American Peat Technology	Aitkin

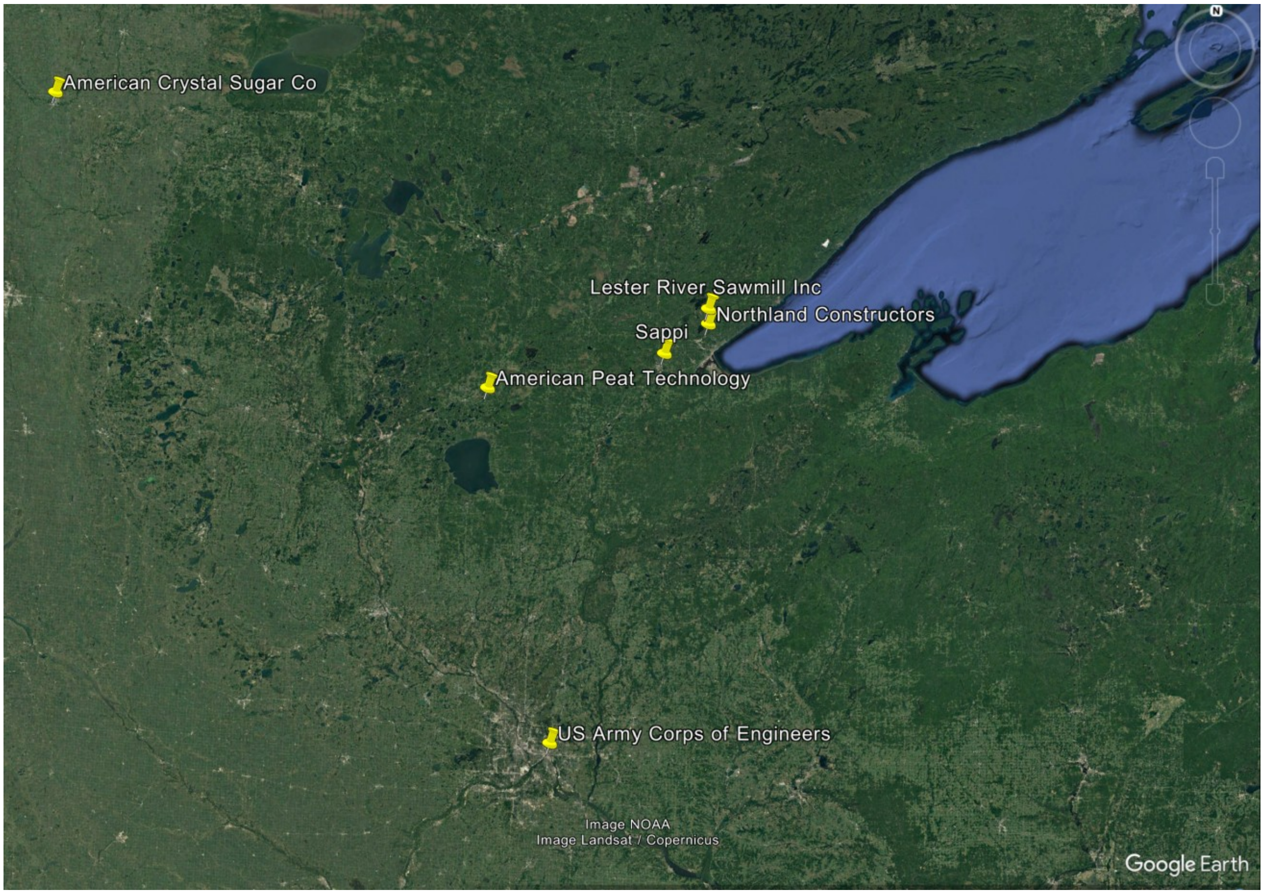

Figure 4.1. Map showing the distribution of waste materials across the state of Minnesota.

4.2 VERSALIME AND BEET TAILINGS

On January 9, 2023, samples of VersaLime and beet tailings were acquired from the American Crystal Sugar Factory. The beet tailings were sourced directly from the waste plant, having undergone recent processing. Meanwhile, VersaLime was obtained from a stored stockpile, as depicted in Figure 4.2.

Figure 4.2. Collection of Beet tailings (L) and VersaLime (R) from an American sugar beet factory.

4.3 BOTTOM ASH, DEGRITTER, AND LIME MUD

The authors collected three waste materials from the SAPPI Cloquet plant on December 12, 2022, including degritter, bottom ash, and lime mud as seen in Figure 4.3. SAPPI Cloquet is an integrated pulp and paper mill known for operating the most modern pulp mill in the United States. Throughout their production process, several waste materials and by-products are generated. Degritter is a material that results from washing incoming logs and typically contains bark, twigs, dirt, and other debris. Bottom ash is a by-product produced by power boilers when burning materials like bark, sludge, and branches. Lime mud is a sludge-like product collected from various stages of the manufacturing process.

Figure 4.3. Picture of Bottom Ash (L), Degritter (M), and Lime mud (R) at the lab.

4.4 RECYCLED CONCRETE AGGREGATE

Several 5-gallon pails of recycled concrete aggregate were collected from the Northland Constructors' storage site at Northland Pier in Duluth, MN on December 13, 2022, and May 22, 2023. All the material was less than 2 in diameter, 64% was less than ⅜-in, and 23% passed through a 20-mesh sieve. Most of this aggregate is sourced from the removal of old concrete roadways before new roadway construction. Northland Constructors has a portable plant to crush and screen this material so it can be used in new construction projects as aggregate. Figure 4.4 shows the collected material.

Figure 4.4. Picture of Recycle Concrete Aggregate at the lab.

4.5 PINE SAWDUST AND ASH SAWDUST

Several 5-gallon pails of green pine and ash sawdust, shown in Figure 4.5, were collected from Lester River Sawmill in Duluth, MN. The sawdust is a byproduct of lumber milling and is simply stored outside in an uncovered pile next to the mill. The pine sawdust was collected on December 7, 2022; before collection, snow was removed from the outdoor collection pile to access the sawdust underneath. The ash sawdust was collected on May 1, 2023, from the outdoor pile.

Figure 4.5. Picture of Pine Sawdust (L) and Ash Sawdust (R).

4.6 DREDGE SEDIMENT

The U.S. Army Corps of Engineers (USACE) is responsible for maintaining waterways, including the removal of sediment and debris from rivers, harbors, and other bodies of water to ensure safe navigation for ships and boats. Dredge sediment can often be beneficially reused in a variety of ways, primarily as civil engineering applications, for instant shoreline restoration, land reclamation, or construction material. Despite these possibilities, only approximately 70% of the collected sediment is currently being repurposed, leaving room for further exploration of its potential applications. In this study, the authors collected dredged sediment from Wabasha Gravel Pit (Figure 4.6), where the sediment had been accumulating between 1985 and 2011. On November 28, 2022, four buckets of the dredge sediment were collected for lab testing, with an additional 14 buckets collected on May 18, 2023, for use in constructing field experimental plots.

Figure 4.6. Picture of the dredge sediment site at the Wabasha Gravel Pit.

4.7 WASTE PEAT AND BIOCHAR MIX

On May 18, 2023, waste peat and biochar mix were collected from American Peat Technology (APT). APT is a research company specializing in providing peat-based products for pollutant removal. The material collected is a waste stream from their baghouse. In the manufacturing process of the peat/biochar microbial carrier, dryer emissions are directed through a baghouse. The peat/biochar fines that separate from the media during the drying process accumulate in the baghouse and are regularly removed and packaged. Approximately 4,000 pounds of baghouse fines are collected weekly. This waste material is included in the study to explore its potential for reuse. Figure 4.7 shows the waste peat and biochar collected for this project.

Figure 4.7 Waste peat and biochar mix at the lab.

CHAPTER 5: LABORATORY TESTING AND RESULTS

5.1 INTRODUCTION

In this chapter, each waste/by-product was thoroughly analyzed to determine its suitability as a medium in a biofiltration system. This assessment involved physical, environmental, and biological procedures, as outlined in Chapter 3. Following this evaluation, the materials that showed the best performance were chosen. These were then combined into mixes, adhering to the mixing ratios specified by the Minnesota Department of Transportation.

5.2 CIVIL ENGINEERING

5.2.1 Individual Waste Material And By-Product Testing

Based on the laboratory method developed by Johnson et al. (2017) and described in Chapter 3, the following tests were conducted on the individual waste material and by-products.

5.2.1.1 Moisture Content Test

Test results for moisture content revealed Pine Sawdust as having the highest moisture, whereas Recycled Concrete Aggregate (RCA) had the lowest. For these tests, organic materials were heated at 60 degrees Celsius, and inorganic ones at 110 degrees Celsius. Due to unforeseen circumstances, the moisture content for VersaLime was not measured. Detailed information about these moisture content test results is presented in Table 5.1.

5.2.1.2 Gradation Test

Materials were classified according to the Unified Soil Classification System (USCS) based on the results of the gradation test. This classification, along with the gradation test findings, are systematically presented in Table 5.2 and illustrated in Figure 5.1. For this analysis, a specific gravity of 2.65 was assumed for all materials.

Table 5.1. Moisture content for the individual waste/ by-product materials.

MATERIAL	MOISTURE CONTENT (%)
Degritter	78.6
Lime Mud	33.0
Bottom Ash	78.1
RCA	0.6
Pine Sawdust	168
Ash Sawdust	140
Peat/Biochar mix	18.5
VersaLime	-
Dredge Sediment	3.4

Table 5.2. Results from the gradation test.

MATERIAL	USCS CLASSIFICATION
RCA	Well Graded Sand
Bottom ash	Well Graded Sand
Degritter	Poorly Graded Sand
Lime Mud	Well Graded Sand with Silt
Pine Sawdust	Poorly Graded sand
Ash Sawdust	Poorly Graded Sand
Dredge sediment	Poorly Graded Sand
Peat/Biochar Mix	Poorly Graded Sand
VersaLime	Poorly Graded Sand

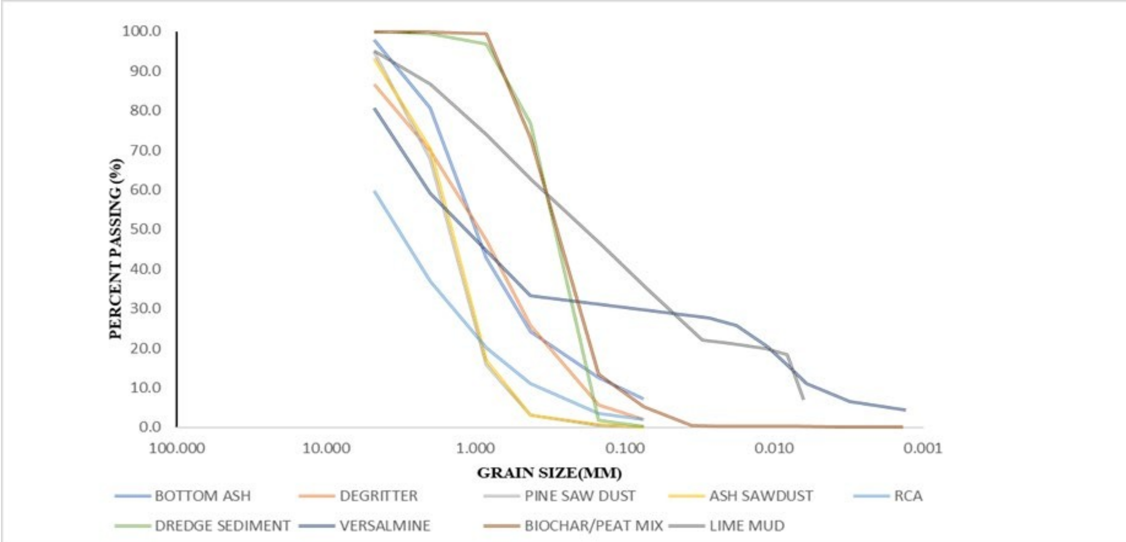

Figure 5.1. Graph showing the particle size distribution for the waste/ by-product materials.

5.2.1.3 Proctor Test

The maximum dry density and optimum water content of the materials were determined using the standard Proctor test. Results from the test, as presented in Table 5.3, indicate that RCA exhibited the highest maximum dry density with an optimum water content of 13.2%. In contrast, pine sawdust recorded the lowest maximum density with an optimum water content of 166.2%. Figures 5.2 through 5.4 illustrate the standard Proctor curves for dredge sediment, VersaLime, and ash sawdust, respectively.

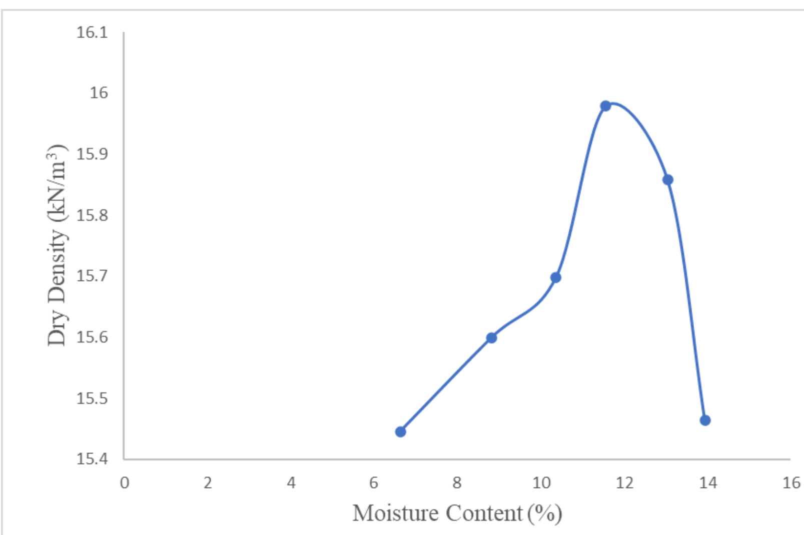

Figure 5.2. Graph showing the standard proctor curve for dredge sediment.

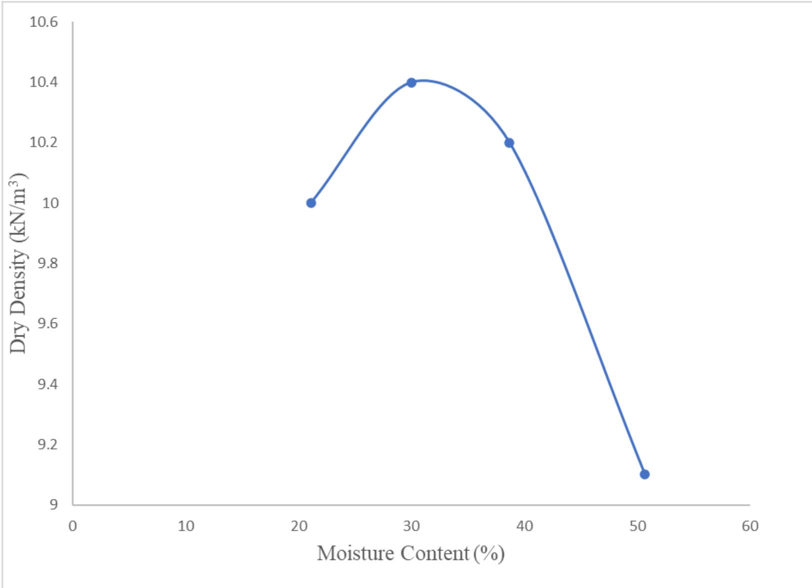

Figure 5.3. Graph showing the standard proctor curve for VersaLime.

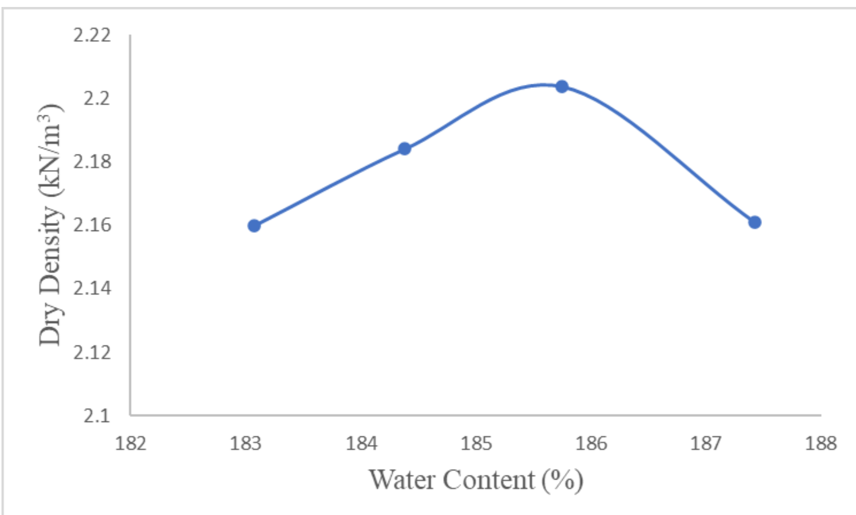

Figure 5.4. Graph showing the standard proctor curve for Ash Sawdust.

Table 5.3. Maximum density and optimum moisture content of the individual waste/ by-product material.

MATERIAL	MAXIMUM DRY DENSITY (kN/m^3)	OPTIMUM WATER CONTENT (%)
Bottom Ash	9.32	45.8
Degritter	7.62	43
Pine Saw Dust	2.18	166.2
Ash Saw Dust	2.21	185.7
RCA	16.62	13.2
Dredge Sediment	15.98	11.8
VersaLime	10.40	31
Peat/Biochar Mix	3.99	87.4
Lime Mud	9.80	42

5.2.1.4 Hydraulic Conductivity Test

Constant head and falling head tests were conducted to determine the hydraulic conductivity for the coarse-grained and fine-grained materials, respectively. The results, presented in Table 5.4, indicate that ash sawdust has the highest hydraulic conductivity, while peat/biochar mix has the lowest. Upon comparing these results to the minimum requirement of $7.1 * 10^{-4}$ cm/sec set by the Minnesota Department of Transportation (MnDOT), it is evident that most of the materials used in this project meet the specified criteria. However, lime mud, peat/biochar mix, and VersaLime do not meet MnDOT's minimum hydraulic conductivity requirement.

Table 5.4. Hydraulic conductivity of the individual waste/ by-product material.

MATERIAL	TYPE OF HYDRAULIC CONDUCTIVITY TEST	HYDRAULIC CONDUCTIVITY (cm/sec)
Bottom Ash	Falling Head	3.90×10^{-3}
Degritter	Constant Head	8.99×10^{-3}
Pine Saw Dust	Constant Head	8.90×10^{-2}
Ash Saw Dust	Constant Head	3.10×10^{-2}
RCA	Constant Head	3.20×10^{-2}
Dredge Sediment	Constant Head	4.20×10^{-2}
VersaLime	Falling Head	1.22×10^{-4}
Peat/Biochar Mix	Falling Head	5.88×10^{-4}
Lime Mud	Falling Head	4.30×10^{-4}

5.2.2 CHARACTERIZATION OF ENGINEERED SOIL MIXTURES

Although most of the individual waste materials and by-products used in the project met the minimum infiltration rate set by MnDOT, only five out of the nine materials were chosen to form the engineered soil mixtures. This selection was based on the ability of these five materials to absorb pollutants effectively and to support plant growth. As seen in Table 5.5, the engineered mixes were created by combining 80 percent of the inorganic material with 20 percent of the organic material, following MnDOT guidelines. Due to the limited availability of materials during laboratory testing, only gradation tests and hydraulic conductivity tests were performed on the engineered soil mixtures.

Table 5.5. Engineered soil mixture composition.

ENGINEERED SOIL MIXES
RCA (80%) + ASH SAWDUST (20%)
RCA (80%) + Peat/Biochar mix (20%)
Dredge Sediment (80%) + Degritter (20%)

5.2.2.1 Gradation Test

Following the gradation test conducted on the engineered soil mixtures, the Unified Soil Classification System was applied again to categorize these mixtures and ascertain their particle size distribution. The outcomes of this test are depicted in Table 5.6 and Figure 5.5.

Table 5.6. Results from the gradation test for the engineered soil mixtures.

ENGINEERED SOIL MIXES	UNIFIED SOIL CLASSIFICATION SYSTEM
aRca (80%) + Ash Sawdust (20%)	Poorly Graded Sand
RCA (80%) + Peat/Biochar Mix (20%)	Poorly Graded Sand
Dredge Sediment (80%) + Degritter (20%)	Poorly Graded Sand

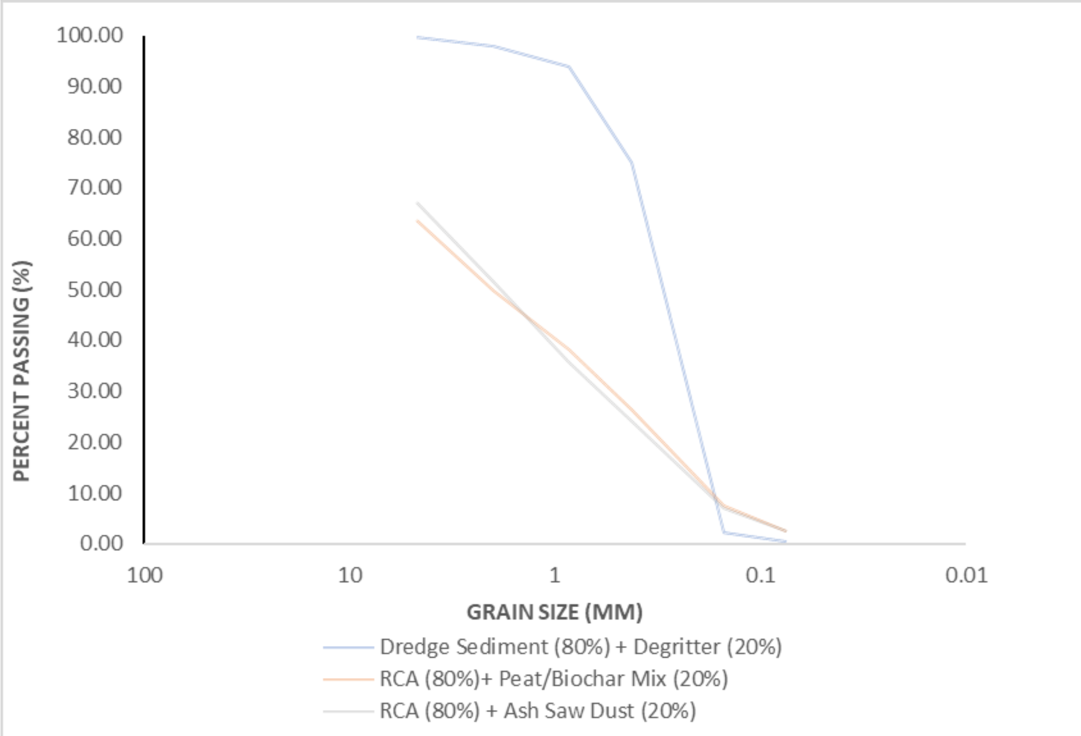

Figure 5.5. Graph showing the particle size distribution for the engineered soil mixtures.

5.2.2.2 Hydraulic Conductivity Test

The gradation test results revealed that the particle size distribution of the engineered soil mixtures is predominantly coarse. Therefore, the constant head method was employed to measure the hydraulic conductivity of these engineered soil mixtures. The findings from this analysis are displayed in Table 5.7.

Table 5.7. Hydraulic conductivity of engineered soil mixtures.

ENGINEERED MIXES	HYDRAULIC CONDUCTIVITY (cm/sec)
RCA (80%) + Ash Saw Dust (20%)	2.10×10^{-2}
Dredge Sediment (80%) + Degritter (20%)	1.81×10^{-2}
RCA (80%) + Peat/Biochar Mix (20%)	1.20×10^{-3}

5.3 ENVIRONMENTAL CHARACTERIZATION

This section summarized the characteristics of the nine waste materials, the pollutant release and adsorption, and the performance in supporting plant growth by a greenhouse test.

5.3.1 Media Characterization

Nutrient and metal contents were measured for seven media (Figure 5.6), except for pine and ash sawdust. Both sawdust materials were analyzed for carbon and nitrogen content after they were composted. Both sawdust materials exhibited acidity, with pH levels below 5, and contained over 50% organic carbon but with low nitrogen content, below 0.1%.

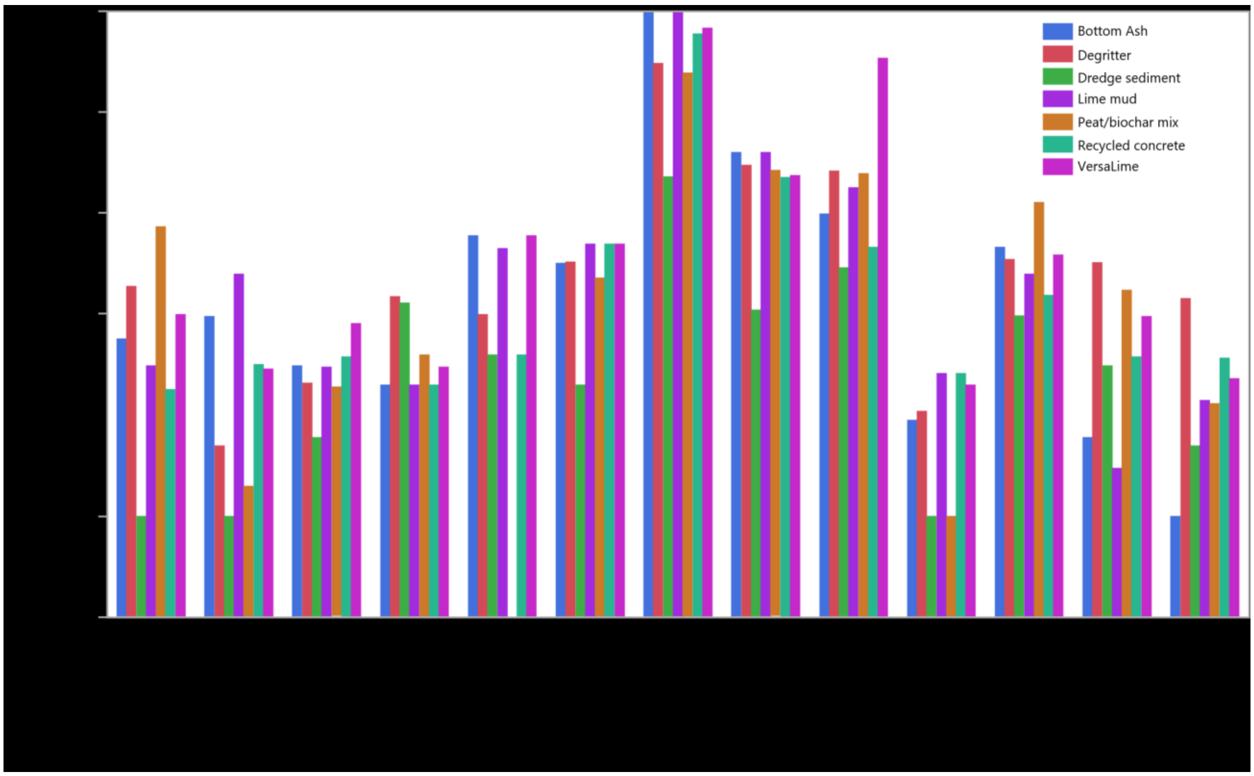

Figure 5.6. The chemical contents of seven waste materials.

Among the seven materials, most displayed a potassium content of 200 ppm or higher, except for dredge sediment, which showed low nutrient and metal levels. Bottom ash and lime mud exhibited high alkalinity, with a pH level of around 12, but these two materials were rich in phosphorus and potassium. Recycled concrete and VersaLime were also alkaline, with pH values around 10. Peat/biochar mix had the highest organic contents, more than 70%, though nitrate and phosphorus levels were relatively low. The degritter had an organic matter content of 18.9, placing it near the category of organic soils.

As dredge sediment and recycled concrete were collected from public works, the possible contents of pollutants were unclear. Both materials were measured for Resource Conservation and Recovery Act (RCRA) metals, Polycyclic Aromatic Hydrocarbons (PAHs), Polychlorinated Biphenyls (PCBs), and volatile organic compounds (VOCs) (Table 5.8). In addition, RCRA metals were assessed in the bottom ash, revealing high levels of barium and chromium, although they remained below soil reference values. Both dredge sediment and recycled concrete showed minimal traces of RCRA metals, with no detectable PCBs or VOCs present. Notedly, PAHs were solely detected in the recycled concrete, albeit well below the soil reference levels. Overall, these three materials exhibited minor traces of contaminants, all falling below-established thresholds. Consequently, they are considered safe for utilization as soil amendments.

Table 5.8. The contents of RCRA metals, PCB, PAH, and VOCs for bottom ash, dredge sediment, and recycled concrete aggregate.

Type	Parameter	Unit	Detection limit	Bottom ash	Dredge sediment	Recycled concrete aggregate	Residential Chronic SRV	Commercial Chronic SRV	Commercial SLV
RCRA metals	Arsenic	mg/kg	1.8	ND	3.6	ND	9	9	5.82
	Barium	mg/kg	0.91	835	73.2	11.9	3100	41000	1684
	Cadmium	mg/kg	0.27	0.48	ND	ND	1.6	23	8.808
	Chromium	mg/kg	0.91	32.1	16	4.7	2.3 (Cr VI), 23000 (Cr III)	62 (Cr VI), 100000 (Cr III)	36.2 (Cr VI), 1000000040 (Cr III)
	Lead	mg/kg	1.8	ND	9.9	0.96	200	460	2700
	Selenium	mg/kg	3.7	ND	ND	ND	78	1200	2.64

	Silver	mg/kg	0.91	ND	ND	ND	78	1200	7.86
	Mercury	mg/kg	0.033	ND	ND	0.022	2.7	3.1	3.290965
PCB		µg/kg	51.6		ND	ND	820	1000	
PAH	Acenaphthene	µg/kg	10.3		ND	67.4	460,000	6,800,000	81,242
	Acenaphthylene	µg/kg	10.3		ND	33.9	NA	NA	NA
	Anthracene	µg/kg	10.3		ND	261	2,800,000	42,000	1,312.816
	Benzo(a)anthracene	µg/kg	10.3		ND	592	NA	NA	NA
	Benzo(a)pyrene	µg/kg	10.3		ND	550	2,000	23,000	1,410
	Benzo(b)fluoranthene	µg/kg	10.3		ND	664	NA	NA	NA
	Benzo(g,h,i)perylene	µg/kg	10.3		ND	400	NA	NA	NA
	Benzo(k)fluoranthene	µg/kg	10.3		ND	332	NA	NA	NA
	Chrysene	µg/kg	10.3		ND	584	NA	NA	NA
	Dibenz(a,h)anthracene	µg/kg	10.3		ND	98.7	NA	NA	NA
	Fluoranthene	µg/kg	10.3		ND	1130	210,000	2,700,000	666,000
	Fluorene	µg/kg	10.3		ND	79.6	390,000	5,800,000	110,524

	Indeno(1,2,3-cd)pyrene	µg/kg	10.3		ND	384	NA	NA	NA
	Naphthalene	µg/kg	10.3		ND	40.7	81,000	280,000	4,468
	Phenanthrene	µg/kg	10.3		ND	769	NA	NA	NA
	Pyrene	µg/kg	10.3		ND	967	220,000	3,200,000	435,120
VOC					ND	ND			

ND: nondetectable, meaning below the detection limit

SRV: soil reference value, data were cited from MPCA Soil Reference Values, Tier 1 Spreadsheet, c-r1-01, cited on Nov. 22, 2023

(https://www.pca.state.mn.us/waste/risk-based-site-evaluation-guidance)

SLV: Soil leaching value, data were cited from MPCA Remediation division Soil Leaching Pathway Spreadsheet (SLV-Spreadsheet), c-r1-03, cited on Nov. 22, 2023

5.3.2 Chemical Release From The Media

The potential environmental contaminants release was evaluated by mixing milli-Q water or HPLC water (specifically for the PFAS test only) with the tested nine media. After that, the concentrations of contaminants in the liquid phase were analyzed to determine if any contaminant was released. Detailed procedures are described in Chapter 3. The primary contaminants studied include the most common pollutants identified in stormwater runoff, such as nitrate, phosphate, and metals (copper, lead, and zinc), and emerging contaminants like PFAS.

5.3.2.1 Metals And Nutrients Release

Out of the nine materials analyzed, three (degritter, dredge sediment, and peat/biochar mix) exhibited a neutral leachate with a pH between 6 and 7 (Figure 5.7). Conversely, two sawdust materials demonstrated an acidic release into the water, while four media - bottom ash, lime mud, recycled concrete aggregate, and VersaLime – displayed a pH above 10 while mixing with milli-Q water. These non-neutral properties across six materials suggest their use in a composite mixture rather than individually.

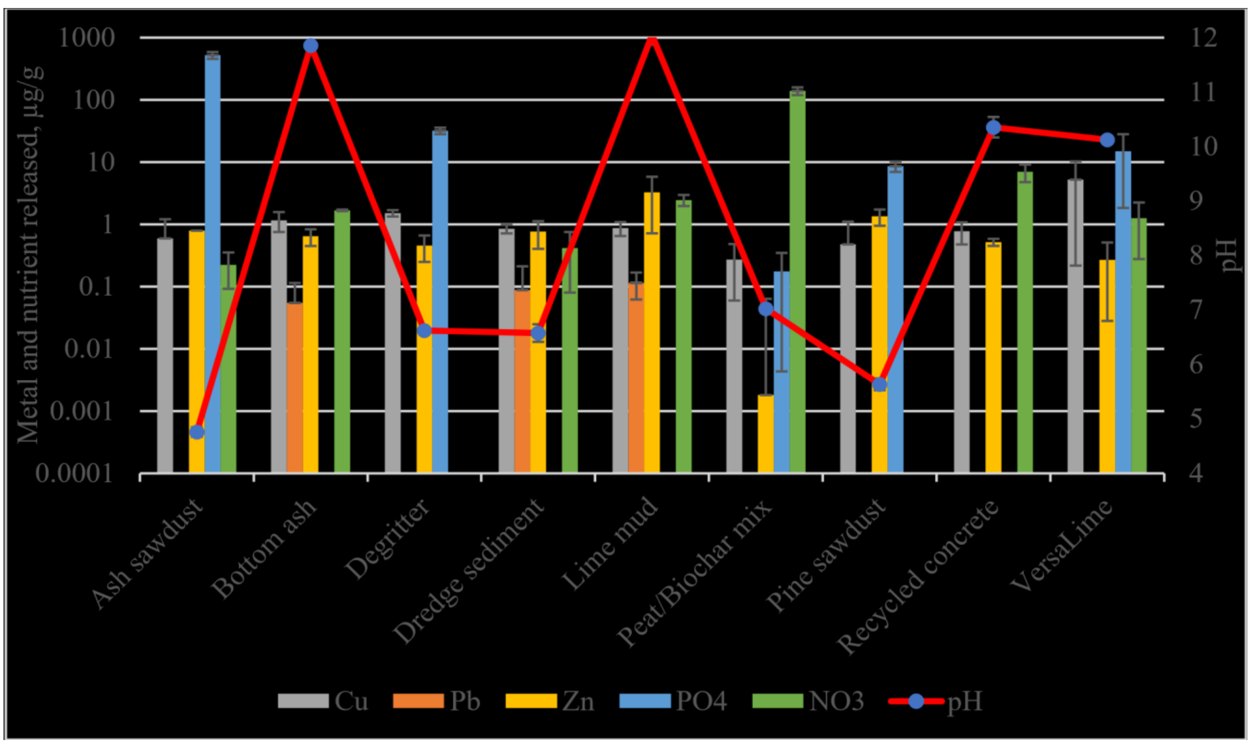

Figure 5.7. Release of metals and nutrients after the materials were mixed with milli-Q water.

Regarding the leaching of copper, lead, and zinc, minimal traces were found across all nine media with VersaLime showing the highest copper levels at around 5 µg/g. The other materials with metal concentration above 1 µg/g included copper in bottom ash (1.2 µg/g) and degritter (1.5 µg/g), zinc in lime mud (3.3 µg/g) and pine sawdust (1.3 µg/g).

However, notable quantities of phosphate leached from ash sawdust, degritter, pine sawdust, and VersaLime. Ash sawdust released phosphate levels of up to 500 µg/g, while concentrations for degritter, pine sawdust, and VersaLime leachate were approximately 32, 8.6, and 15 µg/g respectively. On the other hand, the substantial presence of phosphate in the leachate suggests these materials could serve as a potent source of phosphorus for plant growth. As another nutrient, nitrate release was primarily observed in the peat/biochar mix, reaching a concentration exceeding100 µg/g. In contrast, the release from the remaining materials was below 7 µg/g.

5.3.2.2 PFAS Release

The assessment of PFAS potentially released from the waste materials was conducted through lab batch testing. Given the extensive range of chemicals within the PFAS group, this test specifically examined the potential release of 18 species (Table 5.9). Out of the 18 species, 13 demonstrated a spike recovery rate falling between 50% and 150%. This indicates that accurate measurements were achieved for these species. However, the remaining 5 species exhibited measurement results that were biased either low or high.

Notably, three PFAS species (PFBA, PFHxA, and PFOA) were detected in the blank control samples, suggesting potential contamination from the containers or the experimental process. If the concentrations measured in samples were less than twice the concentrations measured in the blank control, no leaching of these species from the studied materials could be identified. The released PFAS concentrations were calculated based on the mass (approximately 5 grams) of solid material added, providing a measure of mass PFAS released per gram of studied materials (Figure 5.8). In general, the amounts of PFAS released from all materials were found to be less than 1 ng/g, which is lower than a representative value of 10 ng/g for municipal solid waste (SWANA, 2023).

Table 5.9. List of PFAS components measured in the leachate solution. Spike recovery was calculated by comparing the concentrations of the EPA standard solution before and after the experiment process.

No.	PFAS compound	Formula	Spike recovery	Detected in blank control?
1	PFBA	C4HF7O2	116.36%	Yes
2	PFPeA	C5HF9O2	115.26%	
3	PFBS	C4HF9O3S	120.11%	
4	PFEESA	C4HF9O4S	97.90%	
5	4:2 FTS	C6H5F9O3S	28.70%	
6	PFHxA	C6HF11O2	109.64%	Yes
7	PFPeS	C5HF11O3S	446.10%	
8	HPFO-DA	C6HF11O3	139.58%	
9	PFHpA	C7HF13O2	100.22%	
10	PFHxS	C6HF13O3S	62.68%	
11	DONA	C7H2F12O4	95.05%	
12	6:2 FTS	C8H5F13O3S	24.14%	
13	PFOA	C8HF15O2	136.50%	Yes
14	PFMBA	C5HF9O3	113.48%	
15	NFDHA	C5HF9O4	106.87%	
16	PFMPA	C4HF7O3	128.33%	
17	3:3FTCA	C6H5F7O2	156.48%	
18	5:3FTCA	C8H5F11O2	45.32%	

Recycled concrete aggregate and peat/biochar mix exhibited the potential to release multiple PFAS species. The other materials that released a very small amount of PFAS included degritter, ash, and pine sawdust. Due to concentrations in leachate close to the detection limit of the LC-QTOF-MS measurement, large variations were introduced to the measurement results. The outcome can be considered as a preliminary screening of the materials, indicating those with potential for PFAS release.

Further leaching testing with adjusted lab procedures, such as an increased solid-to-liquid ratio or increased liquid volume, will be recommended to obtain more accurate results.

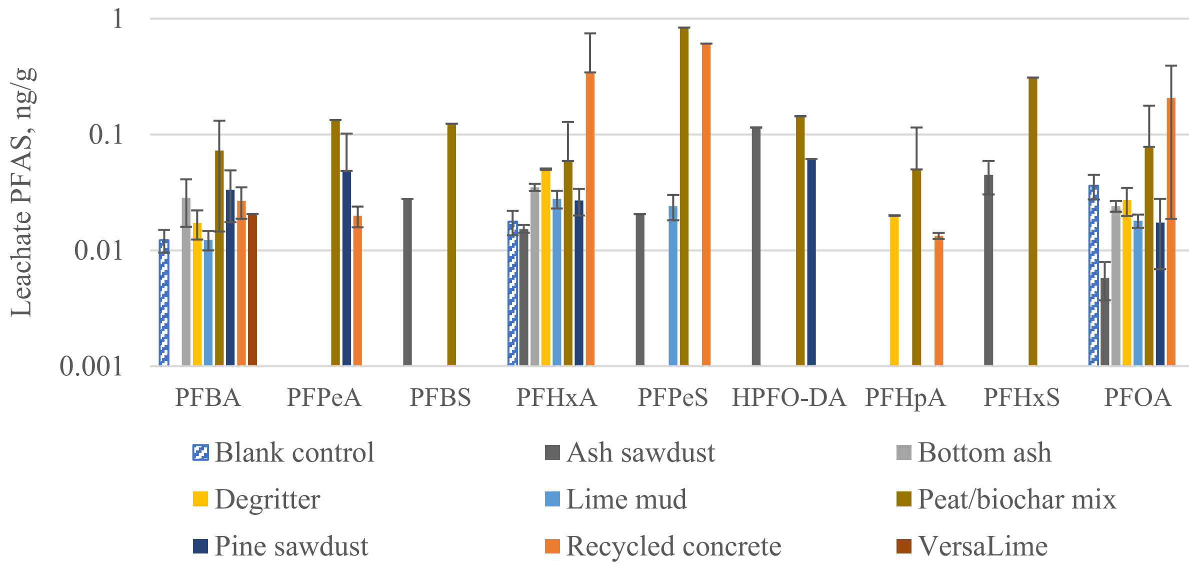

Figure 5.8. The PFAS contents measured in the leachate by mixing 5 grams of studied material with 50 ml HPLC water. The blank control was the sample with HPLC water only and was conducted by the same experiment procedure.

5.3.3 Chemical Removal By The Media

Nutrient and metal removal capabilities were assessed by mixing the materials with lab-synthesized stormwater at various concentration levels, designed to mimic the typical concentrations found in stormwater runoff. The procedure was the same as the release testing, albeit employing distinct solutions for the assessment.

Among the three metals (copper, lead, and zinc), lead was the most easily removed metal by six media, with an average removal ratio consistently surpassing 98%. This effective removal was observed when the materials were mixed with solutions containing lead within the range of 15 µg/L to 5 mg/L (Figure 5.9). The six media included two types of sawdust, degritter, peat/biochar mix, recycled concrete aggregate, and VersaLime. In contrast, the remaining three materials (bottom ash, dredge sediment, and lime mud) achieved a somewhat lower average ratio, ranging from 65% to 80%.

In contrast, to lead, the reduction ratios observed for copper and zinc were relatively lower, averaging between 50% and 80% when mixing with the solutions at the concentration ranges of 0.035-7 mg/L for copper and 0.07-10 mg/L. The dredged sediment exhibited the lowest removal ratios, below 20% reduction ratios for both copper and zinc. Overall, the peat/biochar mix demonstrated the highest adsorption capacities for all three metals across the simulated concentration ranges.

In the absence of plant update, the reduction ratios of nutrients remained generally low for most materials within the examined concentration ranges of approximately 0.075 - 65 mg/L for phosphate and 0.02 - 100 mg/L for nitrate. Notably, VersaLime exhibited an exceptional reduction ratio exceeding 90%. Conversely, the other eight materials demonstrated a removal efficiency of 40% or less for nitrate, and this percentage decreased with rising concentrations in the stock solution.

Interestingly, the reduction ratios of phosphate contents were strongly related to the solution pH, showing an elevated reduction ratio at higher pH levels (Figure 5.10). Both bottom ash and lime mud displayed exceptionally high removal properties, surpassing 90% for phosphate. This can be attributed to their strong basic properties (pH>12), which enhanced precipitation reactions. In the case of recycled concrete aggregate and VersaLime, with pH levels around 10.5, the phosphate reduction ratio was correspondingly reduced to around 70%, still outperforming other neutral or acid media.

The other materials demonstrated phosphate removal percentages ranging from 50% to as low as 10%. The elevated phosphate content in ash sawdust resulted in higher release amounts when the stock solution concentrations were low.

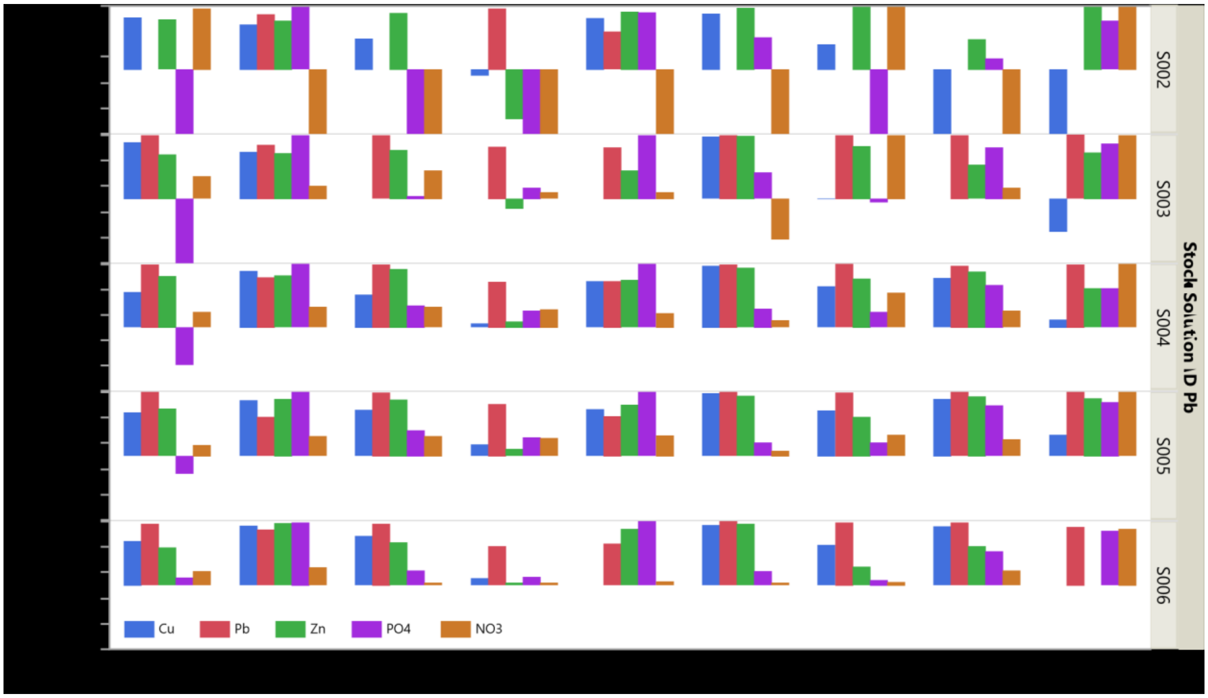

Figure 5.9. The percentage of metals and nutrients removed by the nine studied materials. To test the removal efficiency, five synthesized stormwater with concentrations from low (S002) to high (S006) were mixed with the materials to test the changes of the chemical.

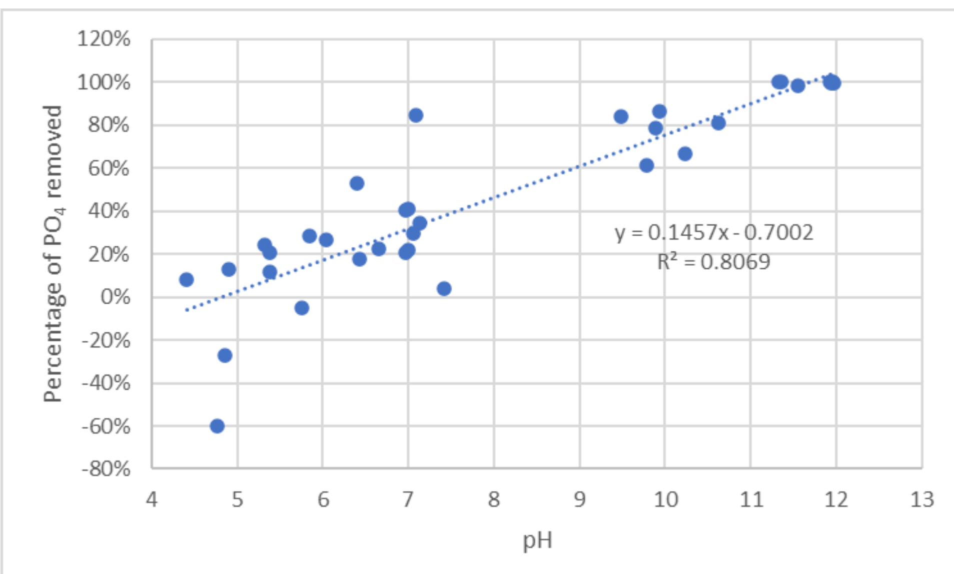

Figure 5.10. The linear fit of the solution pH vs. the percentage of PO4 removed.

5.4 PLANT GROWTH

The plant growth test was conducted in a greenhouse by planting six radish or oat seeds in a single pot. Detailed procedures can be found in the previous chapter. In March 2023, seven different media were tested, except for ash sawdust and peat/biochar mix, which were assessed in October 2023. These two media were collected after the initial batch of the greenhouse testing.

Based on the March test results, three specific mixtures were formulated: a combination of dredge sediment (80%) and degritter (20%), a blend of recycled concrete aggregate (80%) and ash sawdust (20%), and a mixture of recycled concrete aggregate (80%) and peat/biochar (20%). The plant growth test of these three mixtures was conducted in October 2023 as well.

The total growth test was performed for 21 days, but we counted the number of plants observed on the seventh day to represent the germination rate. On the 21st day, the live plant count was repeated, and the height above the media was measured. Plants were then delicately extracted from the media to avoid damaging the roots. The total biomass, encompassing both above-ground plant material and roots was measured after a 48-hour drying period.

For each pot (containing six seeds), data on plant count, total height, and biomass were summarized in Figure 5.11. The bar chart indicated that bottom ash, lime mud, and VersaLime provided minimal support for plant growth through the media alone probably because these media contained high alkalinity. Peat/biochar did support oat growth but with an extended germination period. The remaining media and mixtures demonstrated potential for fostering the growth of both oats and radishes.

To further evaluate media performance, a principal component analysis (PCA) was conducted based on four metrics: number of plants on the 7th and 21st days, total biomass, and total height (Figure 5.12). The PCA plots revealed a strong correlation between total height and the number of plants observed on the 7th day, while biomass showed a stronger correlation with the number of plants observed on the 21st day. For both types of seeds, the materials were categorized into three groups, those that barely supported plant growth, those strongly associated with biomass, and those strongly linked to plant height. Consistent with the bar chart, it was observed that three waste materials—bottom ash, lime mud, and VersaLime—were scarcely capable of supporting plant growth on their own. Instead, dredged sediment, recycled concrete aggregate, and degritter yielded the highest biomass. The three mixtures of organic (20%) and inorganic (80%) media achieved the greatest plant heights, though not the largest biomass. This information indicated that the mixtures could enhance plant germination. Among the nine studied media, oat and radish did grow on peat/biochar, and two types of sawdusts, but at a relatively low germination rate.

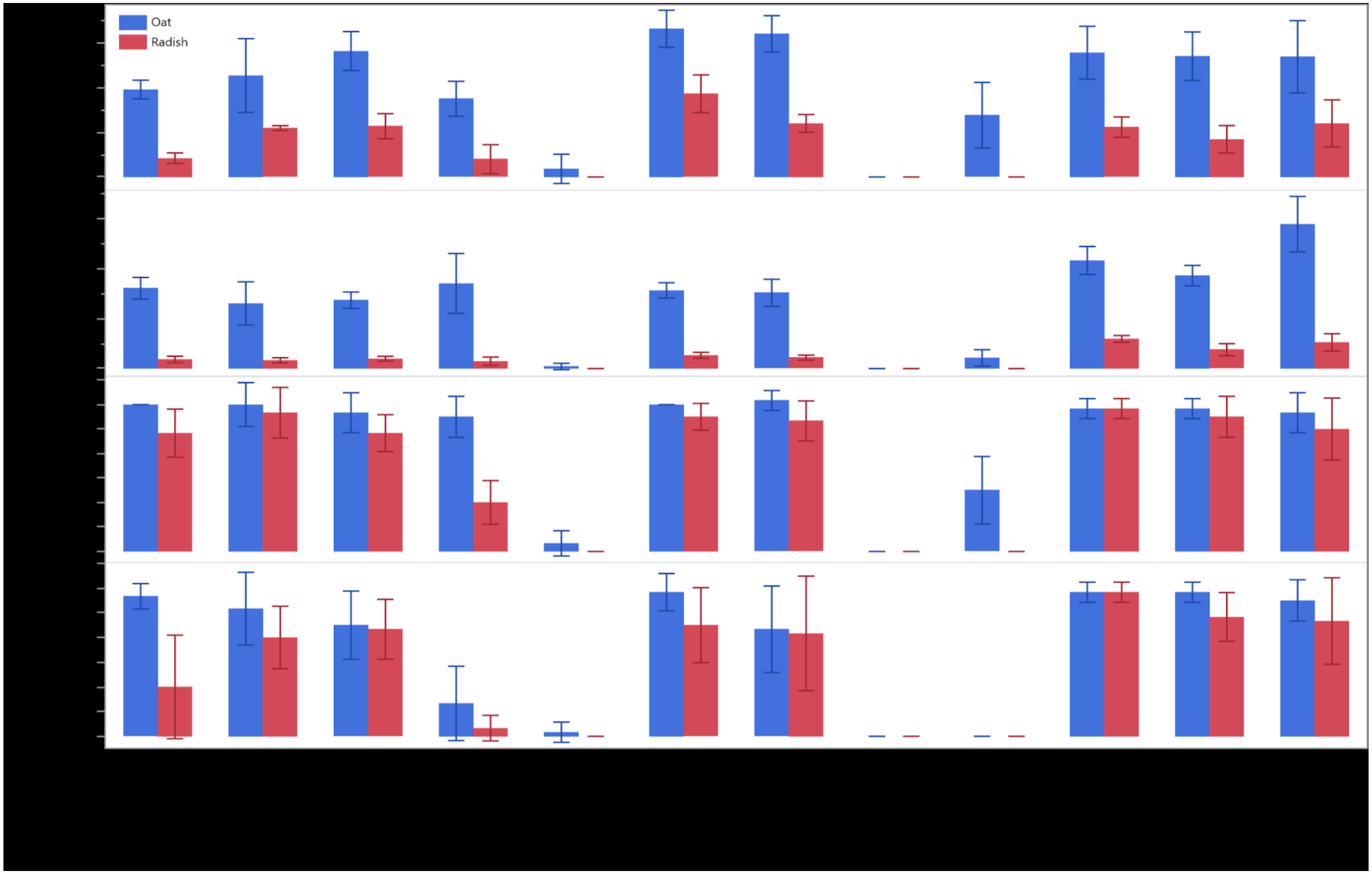

Figure 5.11. The number of plants observed on the 7th and 21st day, and the total plant height and biomass of each pot studied in the greenhouse trail. The error bar represents the standard deviations of each six pots.

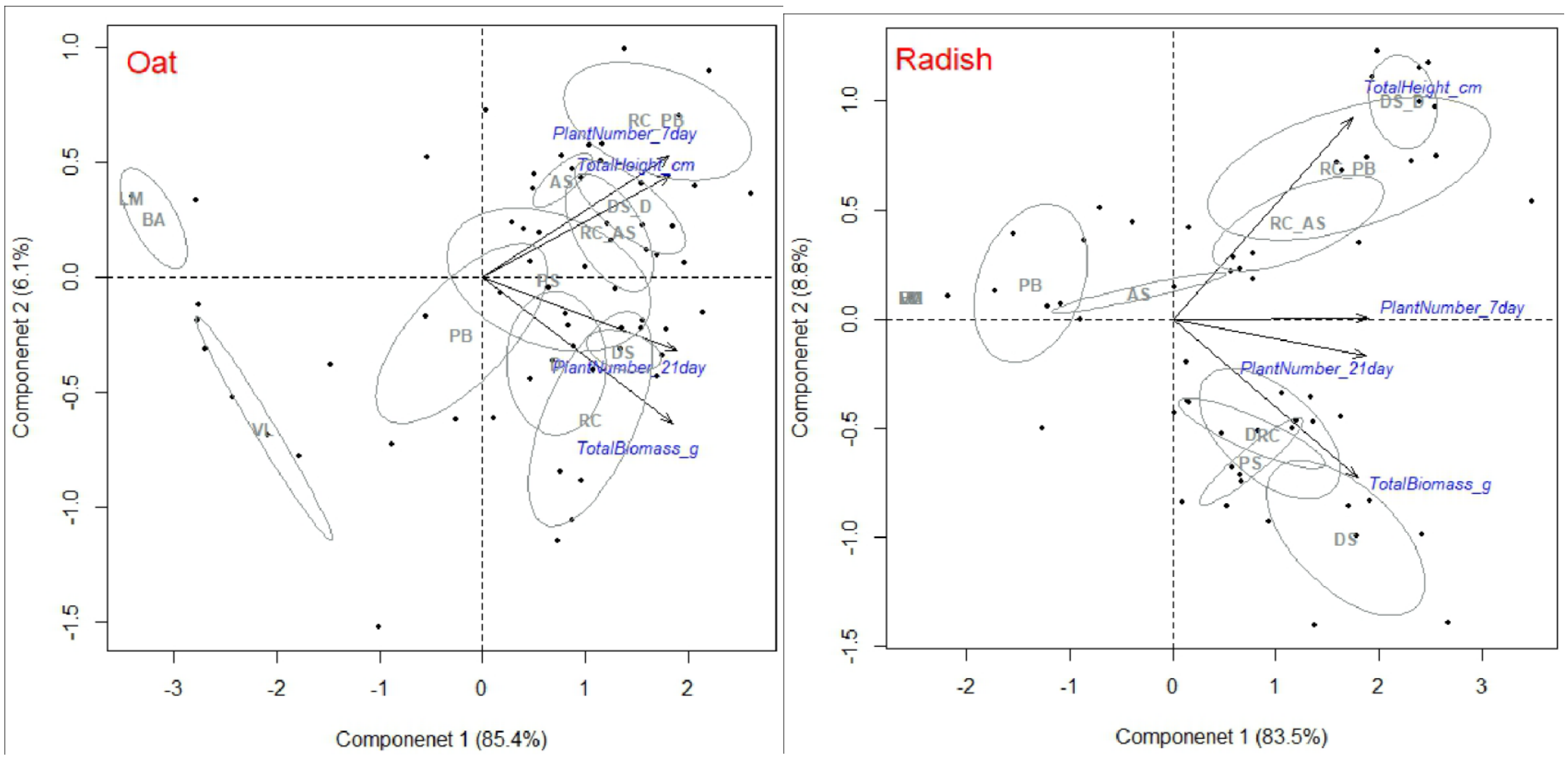

Figure 5.12. PCA plot of the greenhouse trial results for oat and radish using the four variables (plant observed on the 7th and 21st day, total height, and total biomass). The x-axis represents the first PCA component with the variance explained, and the y-axis represents the second PCA component with the variance explained. The ellipses gave the standard deviation of points for each type of material (6 pots each). The material names are: AS – ash sawdust, BA – bottom ash, D – degritter, DS -dredge sediment, LM – lime mud, PB – Peat/biochar mix, PS – pine sawdust, RC – recycled concrete aggregate, VL – VersaLime, DS_D – the mixture of 80% dredge sediment and 20% degritter, RC_AS – the mixture of 80% recycled concrete aggregate and 20% ash sawdust, RC_PB – the mixture of 80% recycled concrete aggregate and 20% peat/biochar. The PCA was conducted in R 4.3.1.

CHAPTER 6: MONITORING OF FIELD PLOTS

6.1 INTRODUCTION

Initiated in 2017, the project involved developing and instrumenting two key sites, known as the Eagle's Nest site and the Natural Resources Research Institute (NRRI) site, to evaluate their effectiveness in infiltration, pollutant removal, and nutrient provision to plants in the biofiltration setups. Monitoring activities at the NRRI sites spanned from 2017 to 2023, while the Eagle's Nest site was under observation from 2018 through 2023. In 2023, six new experimental plots were constructed in the NRRI parking lot, adjacent to the seven existing plots. Pairs of plots were designed to use the same waste/by-product mixture type. This report also includes the monitoring outcomes derived from these newly built sites.

6.2 SITE DESCRIPTION

6.2.1 NRRI Experimental Plots

Experimental plots were established along the northwest slope of the NRRI parking lot, featuring a total of 13 plots. In October 2016, three plots were constructed with a mixture comprising 50% compost and 50% natural soil, while another three featured a blend of 50% peat and 50% natural soil. An additional compost-tailing plot was built in 2018, and on May 25, 2023, six new plots were added. The new plots comprised one organic and one inorganic material blended at a ratio of 20:80 by volume. Three mixtures (one replicate for each) were prepared, including 20% peat/biochar with 80% recycled concrete aggregate, 20% degritter with 80% dredge sediment, and 20% sawdust with 80% recycled concrete aggregate.

All the experimental plots, both old and new, were built with the same dimensions, 3 ft long x 3 ft wide x 10 in deep, as shown in Figure 6.1. The engineered soil mixtures were applied to the plots and layered to a depth of 6 inches above 4 inches of gravel. The gravel layer was included to promote drainage through an underdrain system, directing collected water samples into jars for lab analysis.

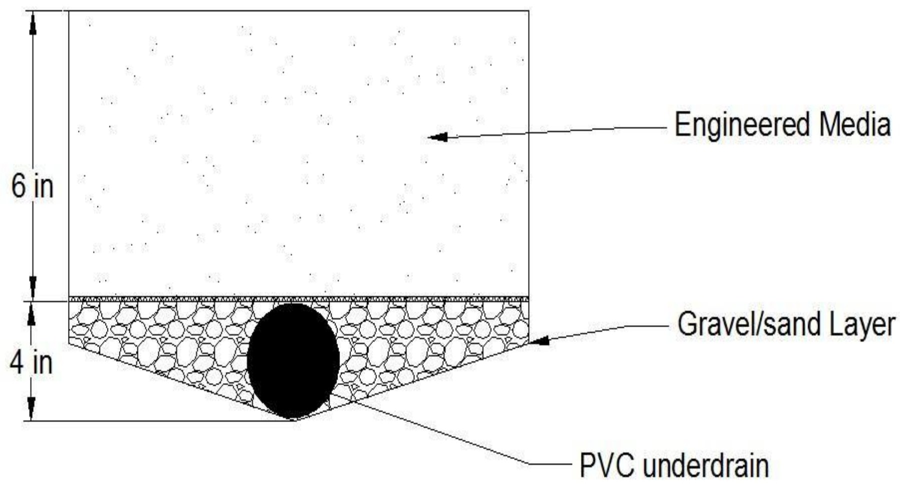

Figure 6.1. Cross section of mixed media pilot plot (adapted from Johnson et al. 2017).

To account for the spatial variations, each type of media mixture was placed in a plot adjacent to two other plots containing different media types, as shown in Figure 6.2. Upon completion of construction, water collection jars were promptly installed. Additionally, instrumentation that monitors rainfall, soil moisture content, and temperature was set up on May 25, 2023.

6.2.2 Eagle's Nest Site

The monitoring instruments of moisture sensors and stormwater collection containers were deployed at the Eagle's Nest site right after the Highway 169 reconstruction was completed in 2018. The media applied to this site includes peat within the slope, and a mixture of sand, peat, and compost at a volume ratio of 80:10:10 in the infiltration bench under the in slope (Figure 6.3).

6.3 STORMWATER RETENTION

The following section describes the civil engineering results of monitoring programs conducted at both the Eagle's Nest and NRRI sites. The amount of water captured following rain events is the controlling property in designing engineered soil mixtures. Accordingly, the researchers monitored water content changes and, using phase diagram relationships determined the height of water retained per unit area of soil.

Figure 6.2. The six new plots were constructed on May 25, 2023. The media used were as follows: 20% peat/biochar with 80% recycled concrete aggregate (plots 1 & 4), 20% degritter with 80% dredge sediment (plots 2 & 5), and 20% sawdust with 80% recycled concrete aggregate (plots 3 & 6). These new plots are positioned adjacent to the previously established seven experimental plots (next to plot 6).

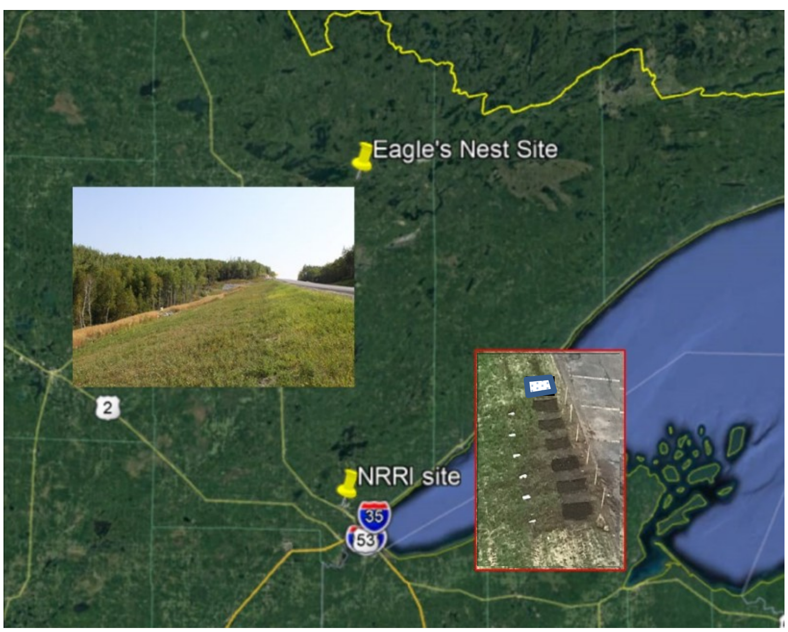

Figure 6.3. Map of the Eagle's Nest site and the NRRI parking lot site. The plots in the NRRI parking lots are old plots. The new six plots were built next to the white plot.

6.3.1 Soil Moisture Change At Eagle's Nest Site

Between 2018 and 2023, a total of 36 moisture sensors were installed at the Eagle's Nest site, with 27 positioned on a slope and 9 within a trench, as illustrated in Figure 6.4. The study aimed to investigate seasonal variations, the relationship between rainfall volume and capture height, and the biofiltration system media's efficiency. The analysis proceeded through three distinct phases. Initially, individual sensors at key locations on the slope (top, middle, base) and one in the swale were evaluated to analyze each gauge station. For gauge station 1, we examined sensors S1-C (Top), S1-E (Middle), S1-G (Base), and T-A (Swale). The second phase involved a comprehensive analysis of each station to observe moisture content fluctuations and the biofiltration media's ability to retain the initial inch of runoff. Lastly, the entire biofiltration system was assessed to determine moisture content trends and the efficiency of retaining the initial inch of runoff. In each case, the change in water content was used to determine the amount of water retained in the system per unit area.

Figure 6.4. The layout of the sensors at Eagle's Nest site in 2022/23 (adapted from Cai et. al, 2021).

Initially, in 2018, the moisture levels both on the slope and in the trench were relatively high, ranging between 40% and 60%. However, there was a noticeable decrease to about 30% in 2019 and 2020, followed by a further reduction to approximately 10-25% between 2022 (Figures 6.5 to 6.7) and 2023 (Figures 6.11 to 6.13) (Cai et al., 2021). This consistent decline in moisture content over the years is likely due to a combination of factors, including changes in the media composition, climatic variations, and alterations in vegetation. Fluctuations in rainfall patterns significantly influence soil moisture; reduced rainfall or extended drought conditions can result in lower soil moisture. Moreover, the soil's physical properties may evolve due to processes such as erosion, compaction, or the loss of organic matter, which diminishes its capacity to retain moisture. Additionally, vegetation type and density also play a crucial role in soil moisture dynamics. Denser vegetation typically enhances moisture retention, whereas a reduction in vegetation coverage can lead to decreased moisture levels. As shown in Figures 6.5 to 6.7, the biofiltration system's effectiveness varies with different rainfall volumes, indicating adaptability to fluctuating rainfall intensities.

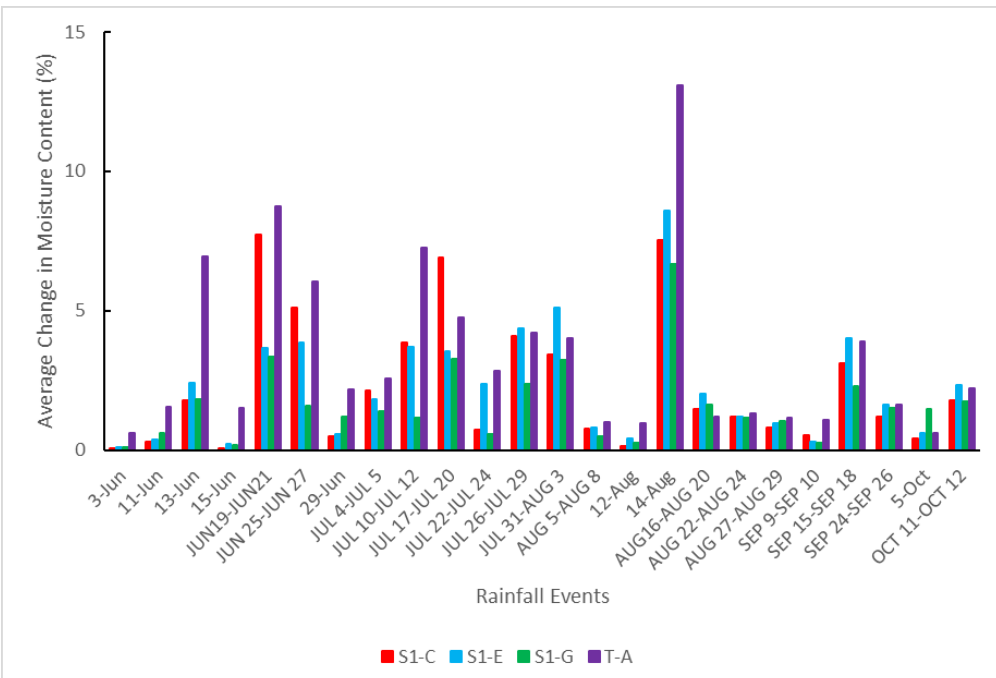

Figure 6.5. Water retention for the Eagle's Nest biofiltration system (Single Sensor-Gauge Station 1) from June 2022 to October 2022.

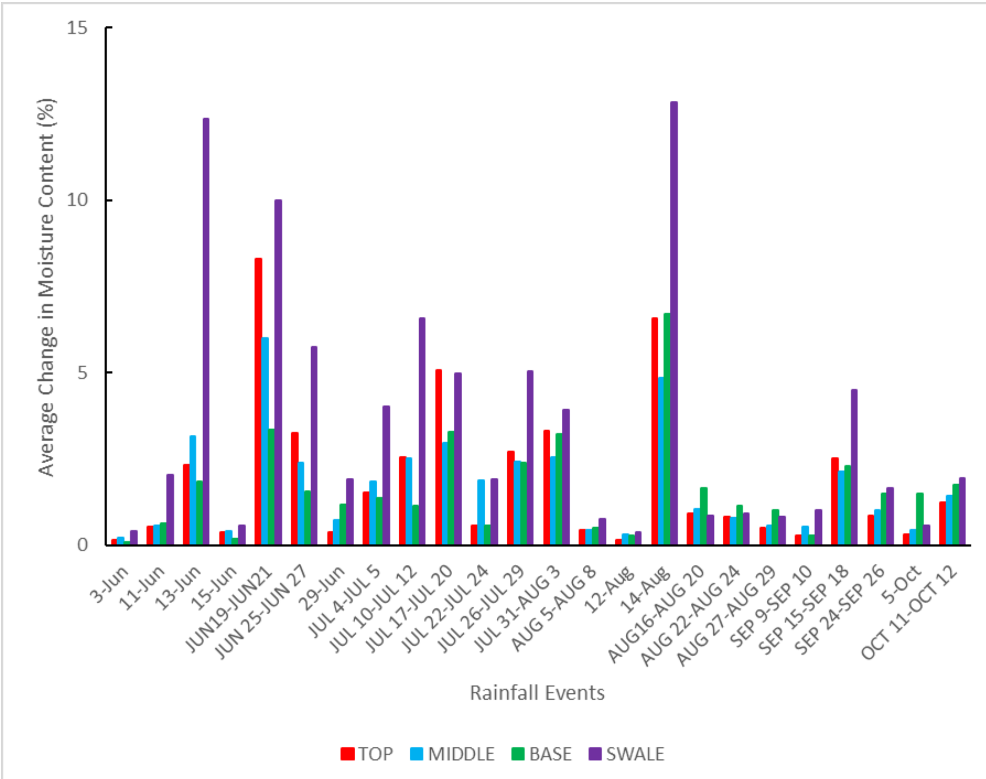

Figure 6.6. Water retention for the Eagle's Nest biofiltration system (Gauge Station 1) from June 2022 to October 2022.

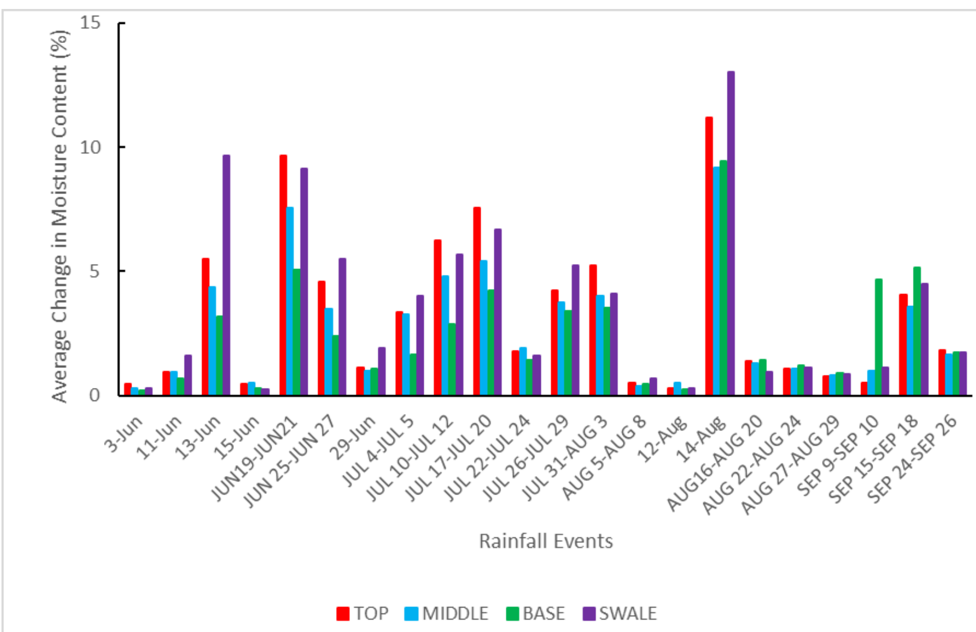

Figure 6.7. Water retention for the Eagle's Nest biofiltration system from June 2022 to September 2022.

Figures 6.8 to 6.10 illustrate the relationship between rainfall volume and the captured rainfall height. These figures employ a distinct black line at a 45-degree angle to represent optimal efficiency, where the captured rainfall height directly corresponds to the rainfall volume. Our analysis, as shown in Figure 6.8, indicates that while data point distribution varies, most data points are concentrated near the efficiency line, indicating effective rainfall capture. This pattern is consistent in Figure 6.9, which focuses on Gauge Station 1, and Figure 6.10, which demonstrates the overall performance of the biofiltration system.

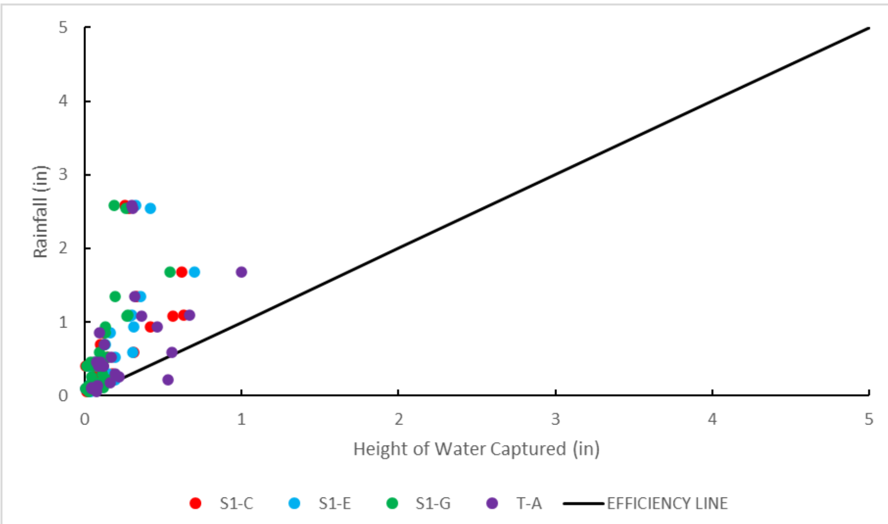

Figure 6.8. Measured rainfall against water captured at Eagle's Nest (Single Sensor-Gauge Station 1) from June 2022 to October 2022. The efficiency line represents the 1:1 ratio line.

Consistent with the trends observed in the 2022 dataset, the 2023 data also showed notable fluctuations in rainfall and height measurements over various months. June recorded the highest average rainfall, whereas October and November demonstrated significantly lower readings in both rainfall and height, clearly indicating a seasonal trend as shown in Figures 6.11 to 6.13.

The 2023 data, like that of the previous year, displays variable distribution. The efficiency analysis demonstrates a strong positive correlation between the amount of rainfall and the average height of rainfall captured, suggesting that greater amounts of rainfall generally lead to higher capture heights as depicted in Figures 6.14 to 6.16.

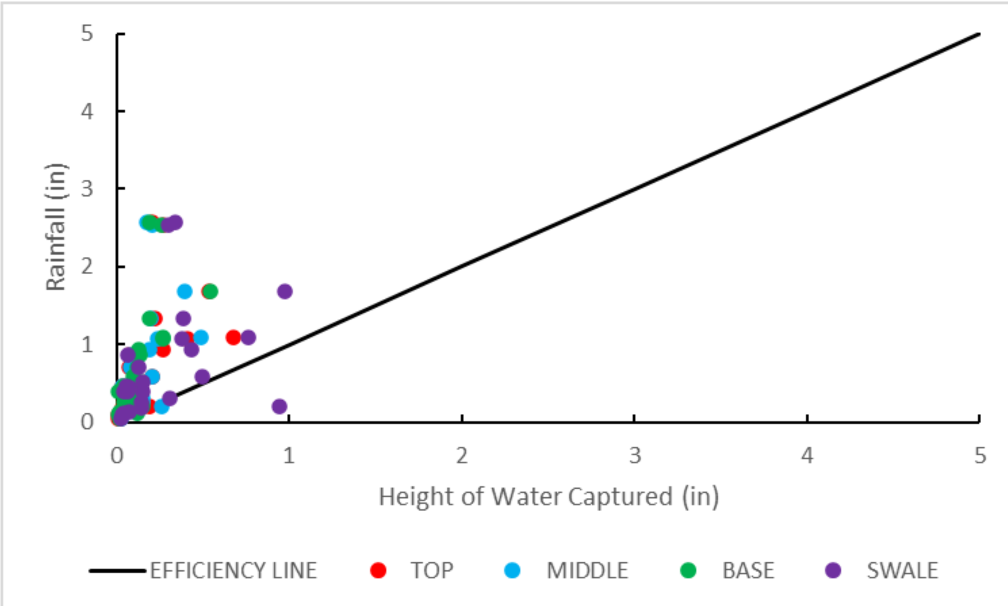

Figure 6.9. Measured rainfall against water captured at Eagle's Nest (Gauge Station 1) from June 2022 to October 2022.

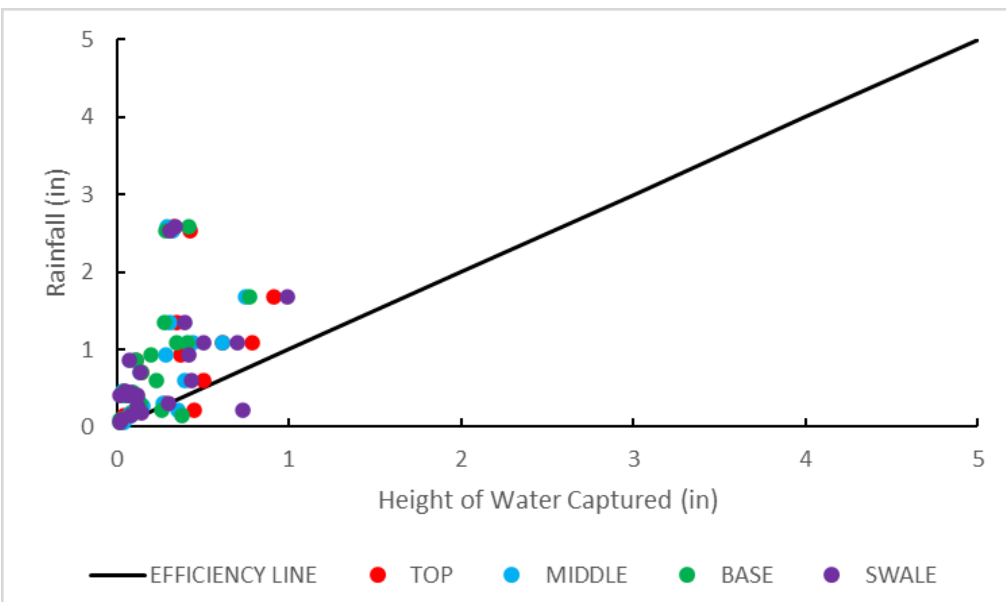

Figure 6.10. Measured rainfall against water captured at Eagle's Nest from June 2022 to October 2022.

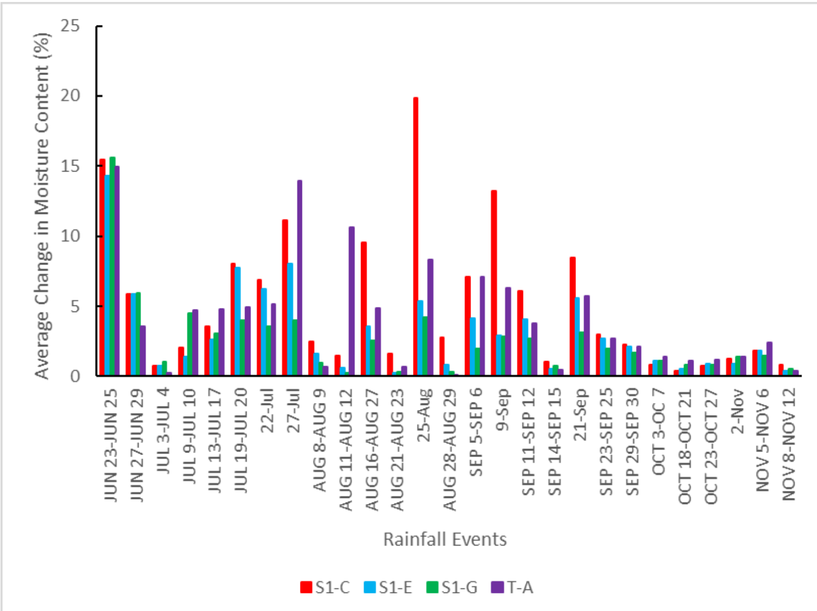

Figure 6.11. Water retention for the Eagle's Nest biofiltration system (Single Sensor-Gauge Station 1) from June 2023 to November 2023.

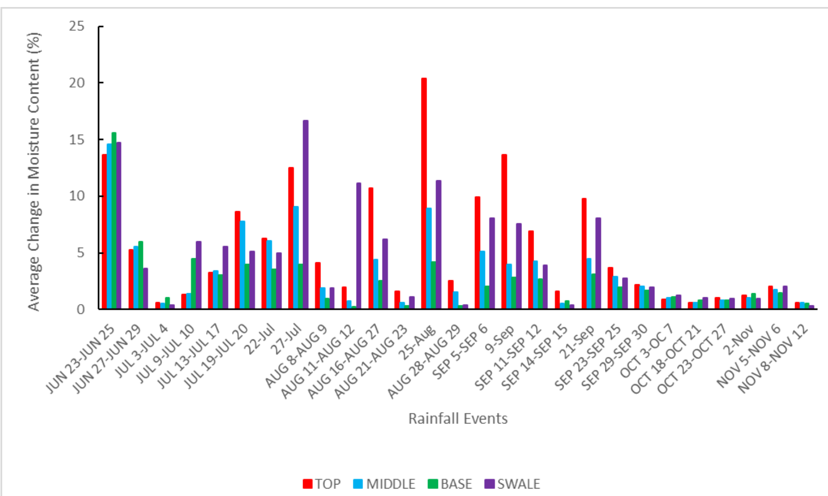

Figure 6.12. Water retention for the Eagle's Nest biofiltration system (Gauge Station 1) from June 2023 to November 2023.

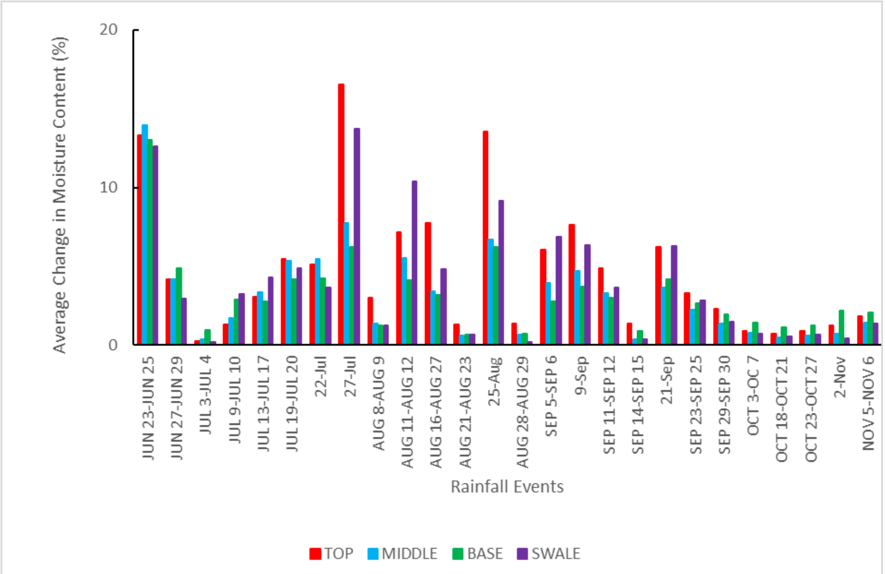

Figure 6.13. Water retention for the Eagle's Nest biofiltration system from June 2023 to November 2023.

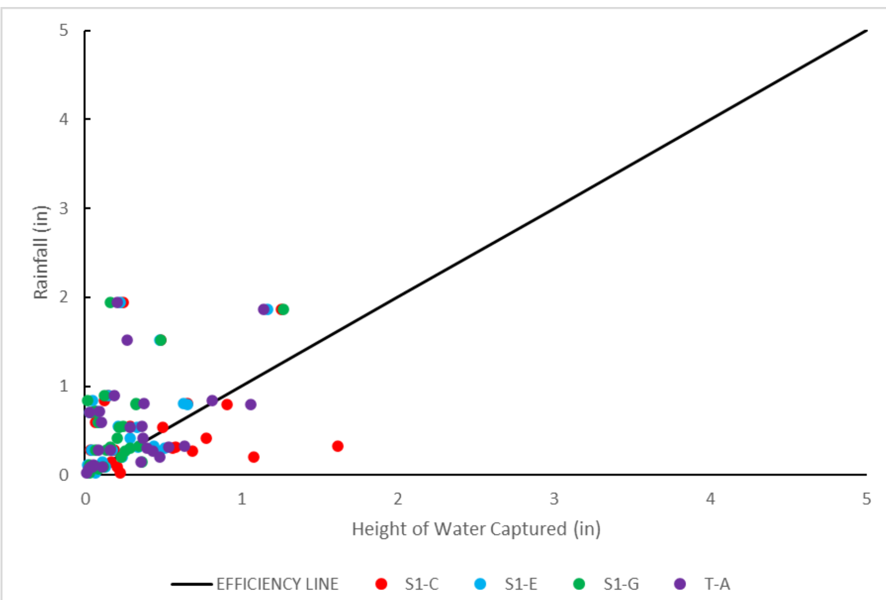

Figure 6.14. Measured rainfall against water captured at Eagle's Nest (Single Sensor-Gauge Station 1) from June 2023 to November 2023.

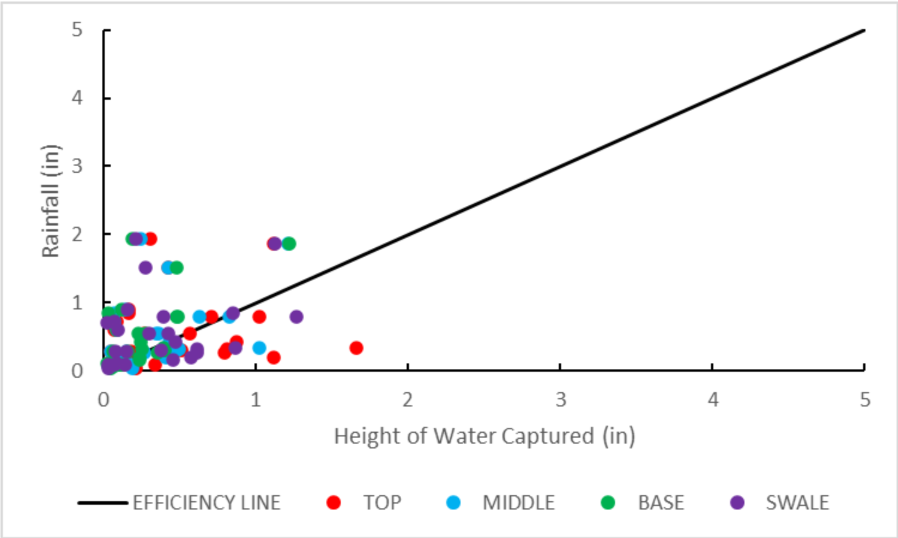

Figure 6.15. Measured rainfall against water captured at Eagle's Nest (Gauge Station 1) from June 2023 to November 2023.

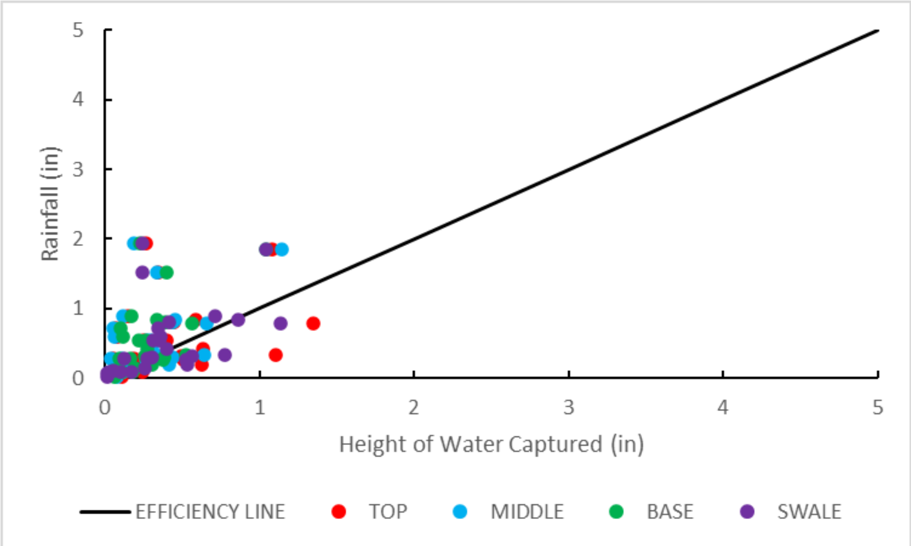

Figure 6.16. Measured rainfall against water captured at Eagle's Nest from June 2023 to November 2023.

In summary, the data from Eagle's Nest for 2022 and 2023 indicates overall successful retention of the first inch of rainfall. The data consistently shows that the system is effective in capturing the initial inch of runoff in most scenarios.

6.3.2 Instrumentation Results At The NRRI Site

Data from our monitoring revealed that only three out of the seven sensors for the old plots, installed for monitoring soil moisture levels, were functional (Figure 6.17). As the engineered soil mixture plots were installed in duplicates, the research team was still able to collect data, but only at the plot. Comparative results with data from 2017 to 2023 significantly deviated from the norm. Furthermore, as depicted in Figure 6.18, a majority of the data points fell below the efficiency line, indicating a weak correlation between rainfall volume and the amount of rainfall captured.

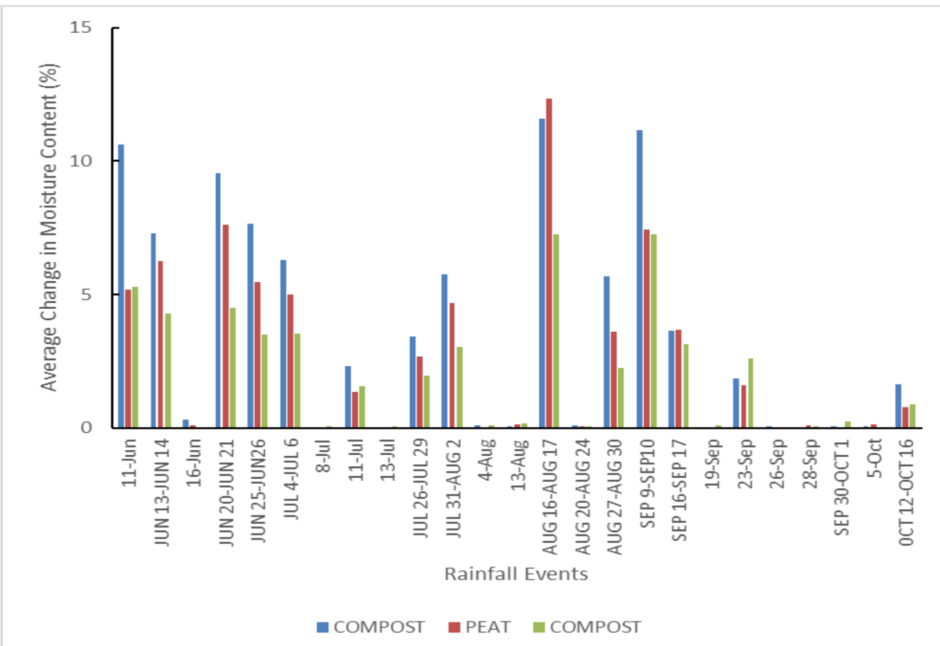

Figure 6.17. Water retention for the NRRI site from June 2022 to October 2022.

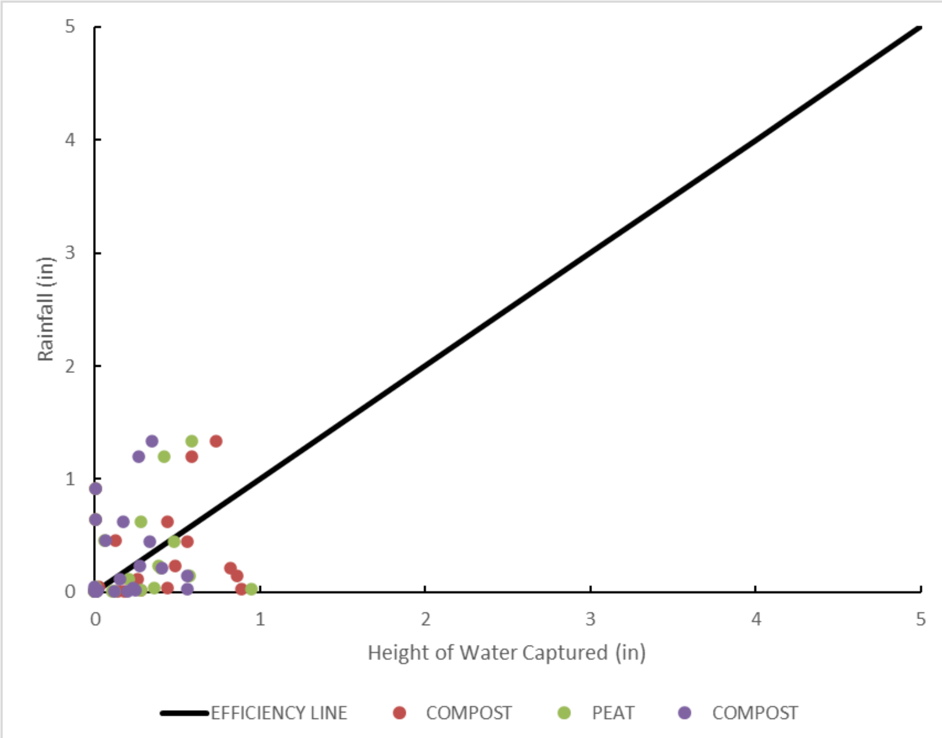

Figure 6.18. Measured rainfall against water captured at the NRRI site from June 2022 to October 2022.

The old plots at the NRRI site, composed of compost, peat, and native soil were efficient in capturing rainfall as seen in Figures 6.19 and 6.20. Each combination of media yielded a unique pattern in capturing rainfall. Notably, data from the peat and compost plots were often nearer to the efficiency line, indicating a higher efficiency in collecting rainwater, particularly in the critical first inch of rainfall that contains most surface pollutants. These observations suggest that peat can be as effective as commercial compost in biofiltration systems, positioning it as a viable alternative.

The field plots were monitored for soil moisture and rainfall to evaluate and contrast water absorption rates. However, due to a malfunctioning rain gauge, we were unable to obtain direct rainfall data for our project and used precipitation data from the Duluth weather station website at the Duluth airport across the street from the monitoring station.

As illustrated in Figure 6.21, September showed a higher total rainfall, with a consequent increase in the average height of captured rainfall, in comparison to August, October, and November. Among the mixes, the dredge-degritter combination demonstrated a superior absorption capability relative to the other engineered soil mixes.

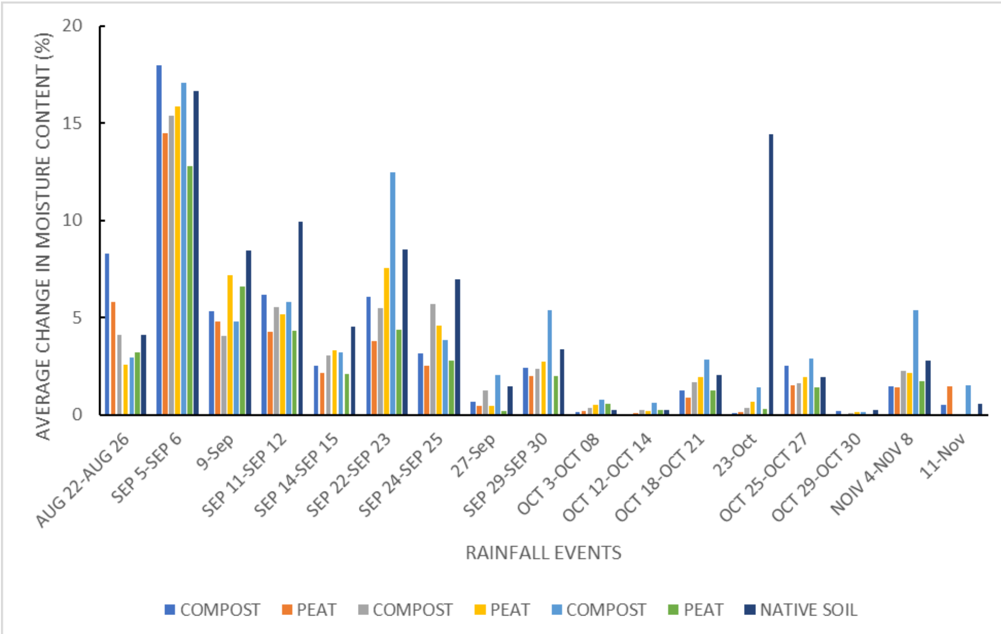

Figure 6.19. Water retention for the NRRI site from August 2023 to November 2023.

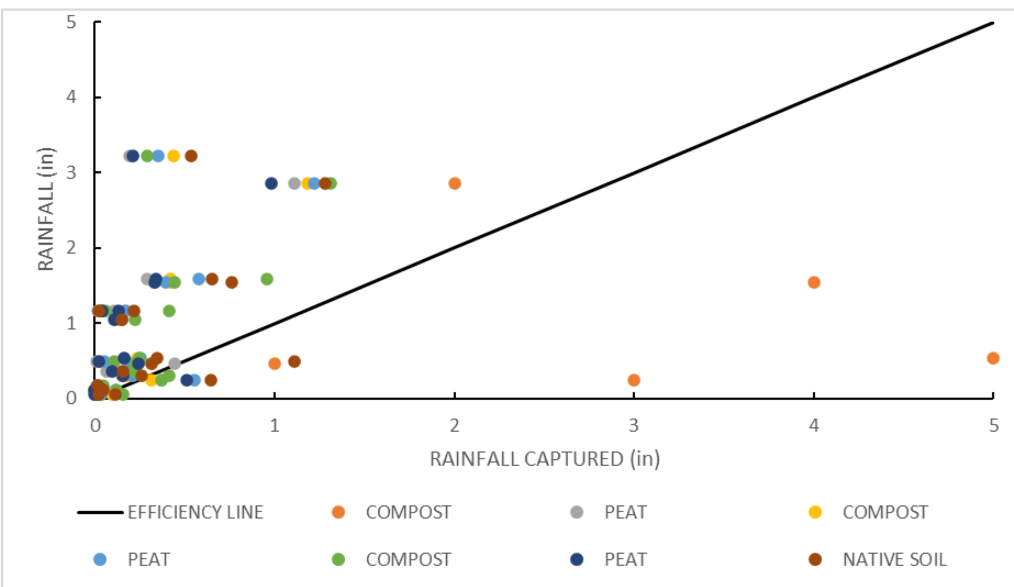

Figure 6.20. Measured rainfall against water captured at the NRRI site from August 2023 to November 2023.

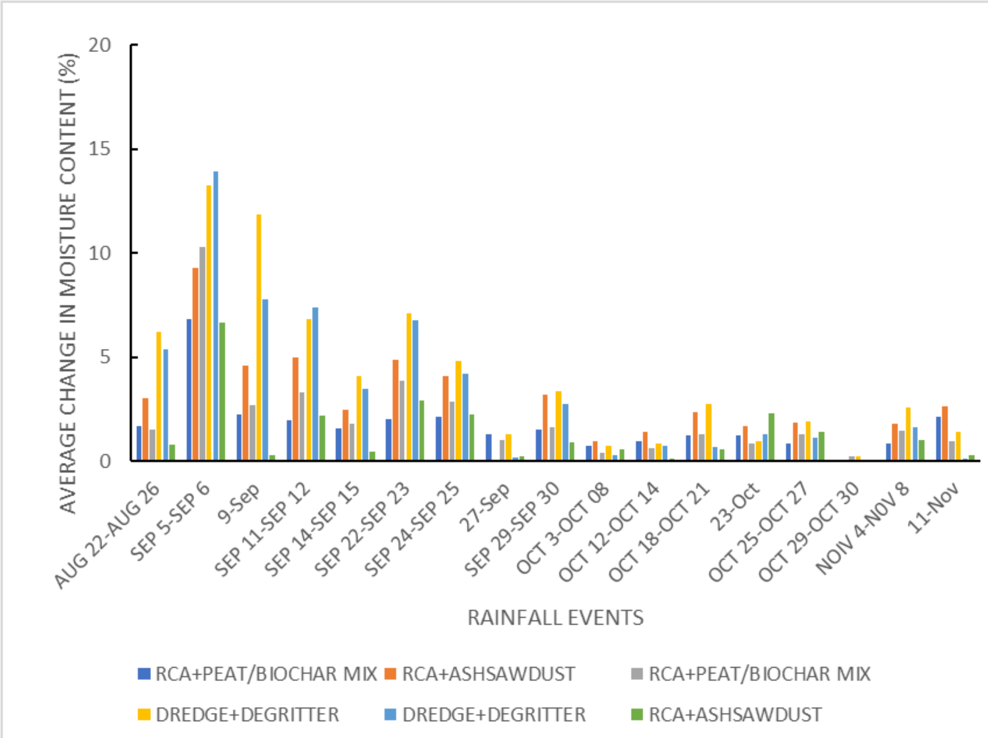

Figure 6.21. Water retention for the NRRI site from August 2023 to November 2023.

To evaluate the effectiveness of our engineered soil mixes in capturing the first inch of runoff, as per MnDOT guidelines, we plotted rainfall quantity against the captured rainfall height as seen in Figure 6.22. This plot depicts the relationship between the volume of rainfall and the corresponding amount of rainfall captured by each sensor. The black line on the plot, set at a 45-degree angle, serves as an indicator of optimal capture efficiency, where the captured rainfall height equals the actual rainfall amount. A positive correlation was observed across all data points, indicating an increase in captured rainfall height with larger rainfall events. The plots generally show most data points nearing the efficiency line, suggesting the mixes' capability to capture small to medium rainfall events effectively as depicted in Figure 6.22. However, in events with rainfall exceeding one inch, only the dredge and degritter mix occasionally managed to capture at least one inch of runoff, achieving this in certain high-rainfall instances.

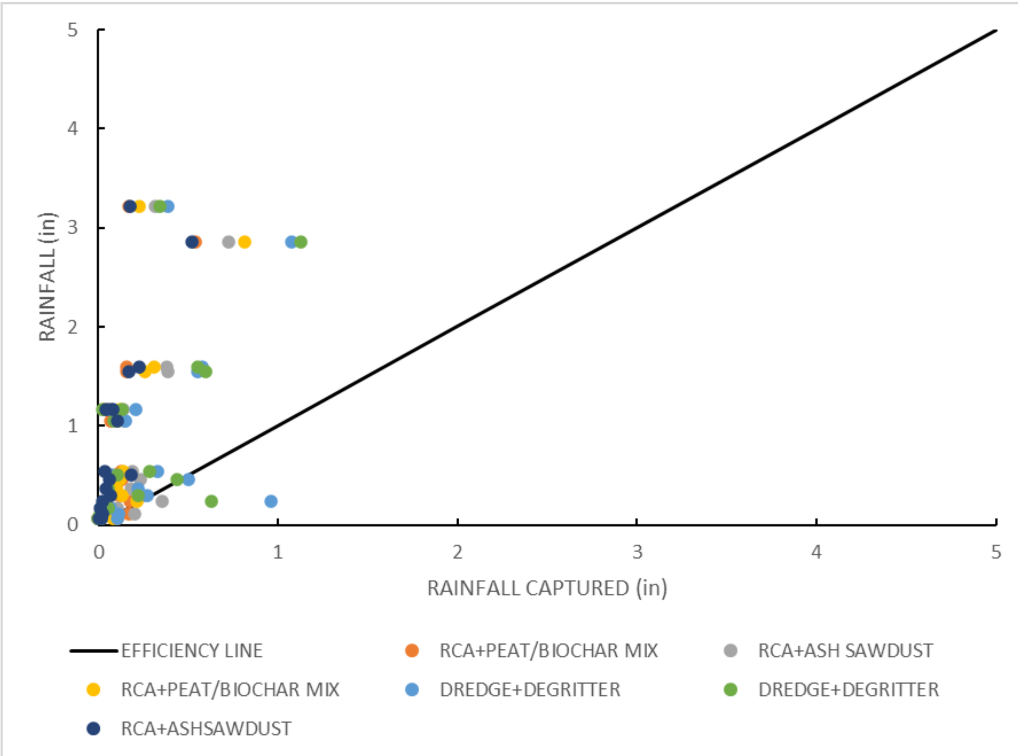

Figure 6.22. Measured rainfall against water captured at the NRRI site from June 2023 to November 2023.

6.4 PLANT GROWTH FOR THE NEW NRRI PLOTS

On June 1, 2023, following the construction of the plots, Prairie Restorations' commercial grass and flower seeds were applied. Each plot received 1.361 grams of grass seed and 0.09 grams of flower seed to achieve a seeding rate of 15 lb/acre for grasses and 1 lb/acre for flowers. After the seeds were applied, a layer of straw-seeding mulch was applied immediately to prevent the loss of seeds by wind and to keep the moisture. Considering the dry weather conditions, watering commenced every workday morning following seeding until June 10th, with each plot receiving 1 gallon of water daily. Unfortunately, limited plant growth ensued after one month, likely due to prolonged dry weather conditions (total rainfall = 0.04 inches from May 25 to June 22). In response to the inadequate growth, on July 6, the same seeds were reapplied, this time doubling the quantity to 2.722 g of grass seed and 0.18 g of flower seed for each plot. Plant cover in October 2023 is shown in Figure 6.23.

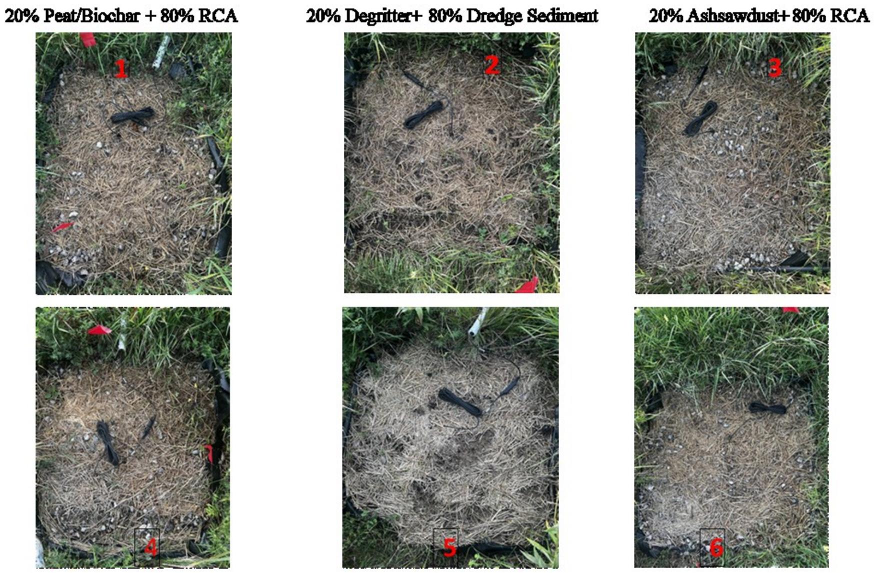

Figure 6.23. Pictures taken on October 3rd, 2023.

Despite being seeded twice during the summer, minimal plant growth was observed in October (Figure 6.23). Several factors could contribute to this outcome, including the extended dry summer period following the seedling in June and July, potential inadequacy in the quantity of seed applied, or insufficient nutrients for seedling development. Based on visual assessment, the abundance of plants varied across the different media types, ranked from the highest to the lowest as follows: 20% degritter with 80% dredge sediment > 20% sawdust with 80% recycled concrete aggregate > 20% peat/biochar with 80% recycled concrete aggregate.

6.5 STORMWATER QUALITY

Stormwater samples were collected from the previously existing seven plots since late 2016 and newly constructed six plots in 2023 during the non-frozen season. Due to the abnormally warm weather in 2023, the stormwater collection activity was extended to the end of the year.

6.5.1 Monitoring Data For Existing Plots In NRRI Parking Lot

The samples collected were analyzed in the laboratory for pH, metal concentrations, and phosphate concentrations. From late 2016, a total of 393 stormwater samples were collected over 88 rain events (Table 6.1).

Over the 7-year monitoring period, some significant trends of chemical concentrations were observed for the experimental plots built with these three materials (Figure 6.24). The pH values significantly declined from approximately 8 to around 7 for the compost and tailing mixture plot, probably due to the oxidization of the sulfide-based minerals. The declining trend of pH was also observed in compost plots but at a moderate rate. Metal release rates were similar across all three media, remaining around 100 ppb for zinc and increasing from below 50 to approximately 400 ppb for copper. A correlation analysis between copper and pH revealed no significant relationship, suggesting other factors, such as the changes in runoff water quality or biological decomposition rates with extended summer periods, might be influencing this increasing trend. Phosphate release from compost and peat plots exhibited a significant reduction, from 5,000 ppb to 700 ppb for compost plots and from 60 ppb to 30 ppb for peat plots. Although a similar declining trend was noted in the compost and tailing mixture plot, the reduction was not statistically significant, and the phosphate concentrations in 2023 were comparable to those in the compost plots.

Table 6.1. The number of rain events each year for stormwater sample collection.

Year	Count of rain events	Start date	End date
2016	1	11/28/2016	11/28/2016
2017	18	4/19/2017	10/3/2017
2018	12	6/4/2018	10/31/2018
2019	17	5/20/2019	10/23/2019
2020	8	7/9/2020	10/16/2020
2021	10	5/23/2021	10/28/2021
2022	13	5/12/2022	11/10/2022
2023	9	6/29/2023	12/27/2023

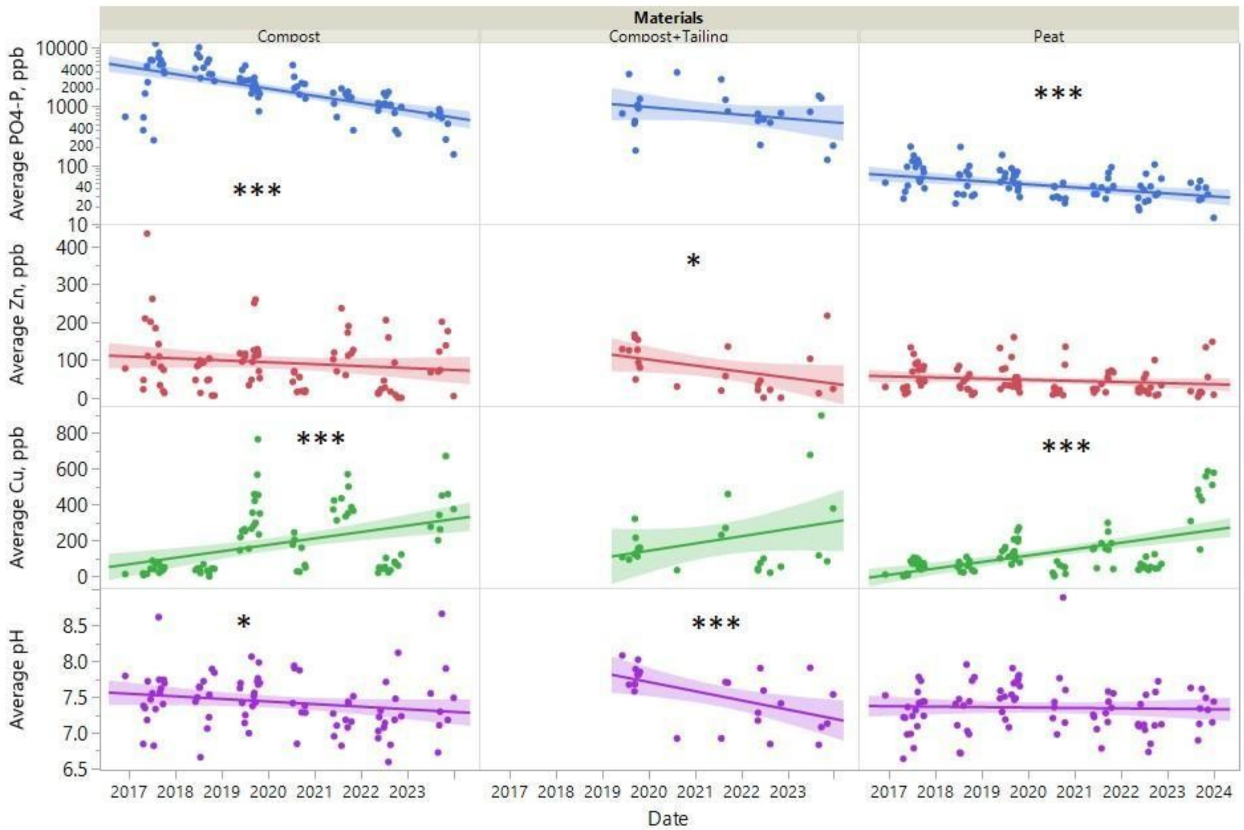

Figure 6.24. The trend of average concentrations of metals, PO4-P, and pH for leachate water was collected from three types of experimental plots. The strongly linear fit ($p<0.05$) was labeled by *, while * indicates a moderated linear fit ($0.05<p<0.1$).**

6.5.2 Monitoring Data For Existing Plots In Eagle's Nest Site

Stormwater monitoring at the Eagle's Nest site began in 2018 immediately following the completion of road construction. However, only a limited number of samples were collected from this site each year, especially for the trench. The stormwater from the trench filtered through the soil media into a perforated underdrain pipe and traveled approximately 20 meters before reaching the collection point. The extended pipe length raised concerns about potential clogging, causing no water sample to be collected from the trench in 2023.

Analysis of the 6-year observation data showed that the in slope above the trench tended to have higher metal concentrations, typically above 100 ppb for copper and zinc (Figure 25). In contrast, the metal concentrations in trench stormwater were usually below 100 ppb and mostly around 10 ppb. Phosphate concentrations across all three sites generally remained below 100 ppb and no significant trends were observed over the six years.

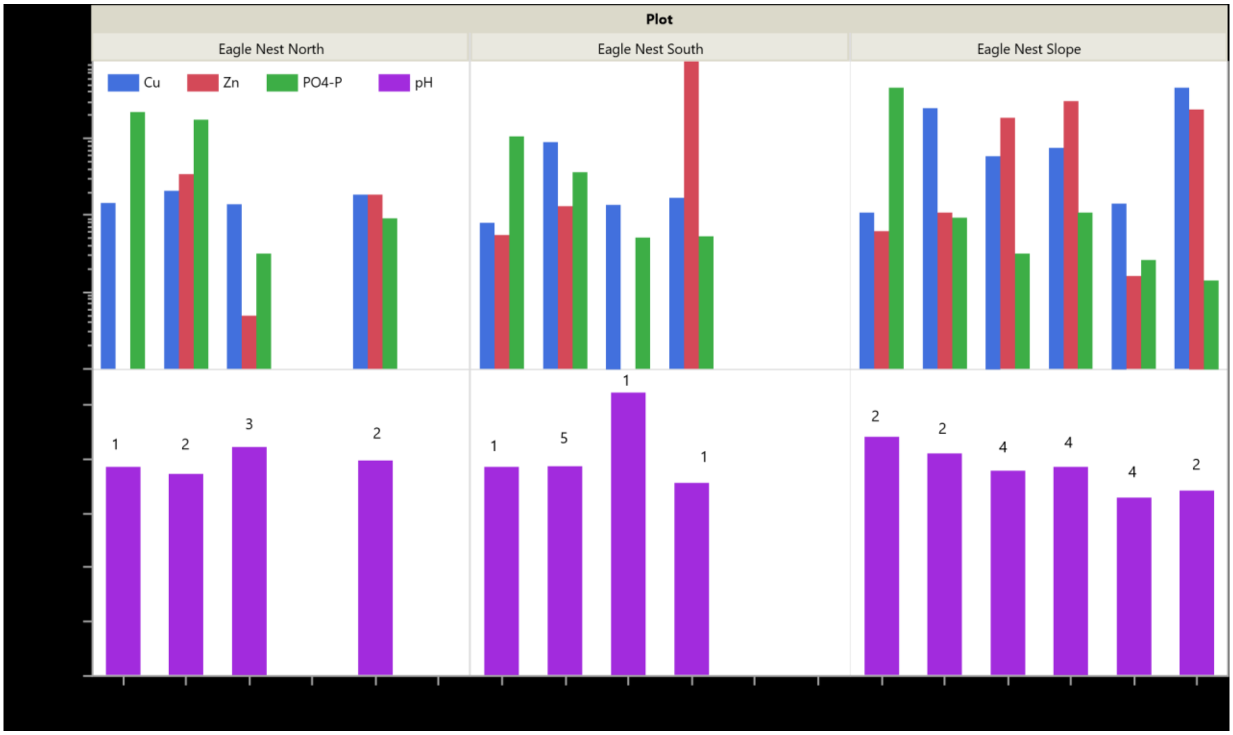

Figure 6.25. The annual mean concentrations of copper, zinc, phosphate, and pH values for stormwater collected at Eagle's Nest site. The number above the pH values bars showed the number of samples collected for analysis. Eagle's Nest North represents the trench located at the north end of the Eagle's Nest site, Eagle's Nest South is also the trench located at the south end of the site, and Eagle's Nest Slope is the roadside in slope above the trench.

6.5.3 Monitoring Data For Newly Built Plots At NRRI Parking Lot

In 2023, stormwater samples were collected during 5-6 rain events, predominantly occurring after September following the extended dry summer. The warm weather also prolonged the final sample collection until the end of December. After the last collection, the sample collection containers remained in the field to capture spring snowmelt samples.

The chemical concentrations of stormwater collected from the three recently built plots (Degritter with dredge sediment mix, peat/biochar with recycled concrete aggregate mix, and sawdust with recycled concrete aggregate mix) were compared with those from previously built plots (compost, compost with tailing, and peat). Generally, the concentration levels of the studied chemicals exhibited similarities between the old and the new plots, characterized by neutral pH values (Figure 6.26). Copper and zinc concentrations were predominantly below 600 ppb and 200 ppb respectively, except for the peat/biochar plots, where copper concentrations ranged between 600 and 1,000 ppb and zinc concentrations ranged from 80 to over 2,000 ppb. Phosphate concentrations for the three new plots displayed large variation, likely influenced by high concentrations detected in the first sample collection. The median phosphate concentrations for the three new plots typically were around 20-30 ppb. Further monitoring is essential to investigate the temporal patterns of chemical concentrations in these new plots.

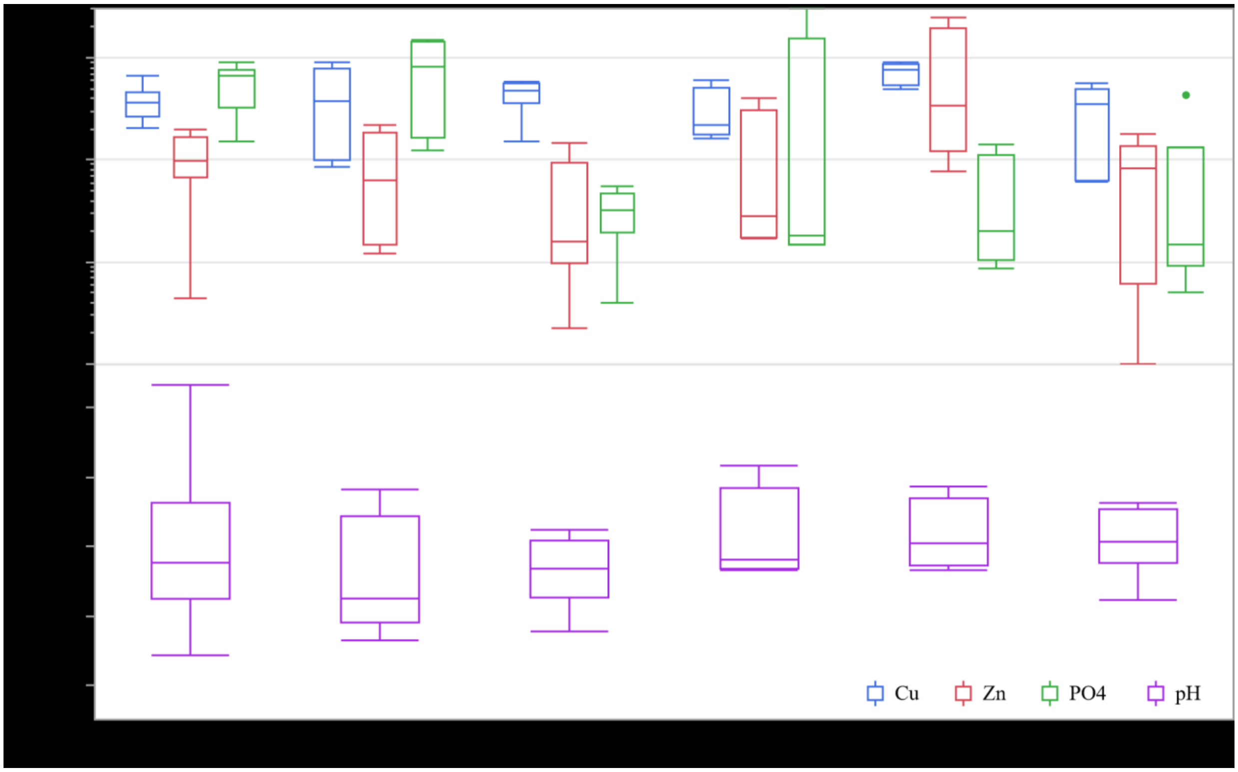

Figure 6.26. The chemical concentrations and pH values of stormwater collected in 2023 for the existing plots (the left three materials) and the new plots.

6.6 SUMMARY

The long-term monitoring data has provided valuable insights, highlighting trends such as declining water retention capacity, reducing phosphorus release from compost and peat, increasing copper levels, and a rise in acidity from tailing waste. These findings are useful in quantifying the prolonged effectiveness of waste materials and estimating their lifetime.

Furthermore, the introduction of new materials enhances the comparative analysis of stormwater treatment among different materials. This comparative assessment facilitates the identification of optimal materials for future applications, contributing to informed decision-making in sustainable waste management practices.

CHAPTER 7: LIFE-CYCLE ASSESSMENT

7.1 INTRODUCTION

The research team completed a preliminary, screening cradle-to-gate life-cycle assessment (LCA) of the three top-performing engineered soil mixes. The system boundary included material and fuel consumption for collection of the materials and transport of the materials to the site where the materials were applied. Because this preliminary screening LCA study was cradle-to-gate, use-phase activities, and disposal/recycling of the engineered soil mixes at end-of-life were excluded. Most of the life cycle inventory (LCI) data was secondary data from the *DATASMART* LCI database (LTS 2020). This study also used the cut-off approach method for recycling and utilized the *LTS 2019 v1.02* (LTS 2019) method to translate the LCI data into environmental impacts; this method combines the *Recipe 2016 Endpoint (H) v1.05* method (Huijbregts et al. 2017) with three endpoint categories (human health, ecosystems, resources) and the cumulative energy demand, climate change, and water use impact categories.

A screening LCA is helpful to identify where in the product life cycle most of the environmental impacts occur, as well as which environmental areas are most impacted. This helps in the definition of the goal and scope of future work, if desirable. The screening LCA may also serve as a guide for a full LCA and allow for the refinement of the goal and scope moving forward while forming the basis of the model for a full LCA. Since a screening-level LCA may use simplified assumptions, the results are only as accurate as those assumptions.

This study was modeled using *SimaPro v9.5.0.0* LCA software (Pré 2016) and followed International Organization for Standardization (ISO) 14044 guidelines (ISO 2006a) for internal screening LCAs; however, this LCA is not ISO-approved. Screening-level LCAs are used for gathering and analyzing internal information allow for assumptions and the use of proxy data and do not usually include the exhaustive sensitivity, consistency, or uncertainty analyses required to comply with ISO 14044 guidelines for public disclosure.

7.2 GOAL AND SCOPE DEFINITION

The first phase of an LCA defines the goal and scope of the study. According to ISO 14044, the goal of the study should specify the intended application, reasons for carrying out the study, the intended audience, and whether the results are intended to be disclosed to the public. The scope describes the most important aspects of the study, including the functional unit, system boundaries, cut-off criteria, allocation, impact assessment method, assumptions, and limitations.

7.2.1 Objective

The objective of this study was to determine the potential environmental impacts of the three top-performing engineered soil mixes. The results could be used to inform potential users and their stakeholders of the potential environmental "hot spots" of utilizing these soil mixes.

7.2.2 Function

The function of the engineered soil mixes is to act as a medium in a biofiltration system when applied along roadways.

7.2.3 Functional Unit

A functional unit identifies the primary function(s) of a system based on which alternative systems are considered functionally equivalent (ISO 2006b). This facilitates the determination of reference flows for each system, which in turn facilitates the comparison of two or more systems. Based on the identified function, the following functional unit was used to determine the reference flows: one ton of engineered soil mix.

7.2.4 System Boundaries

System boundaries are established in LCA to include significant life cycle stages, unit processes, and associated environmental flows in the analysis. This lays the groundwork for a meaningful assessment where all important life cycle stages, and the flows associated with each alternative, are considered. Included in the system boundary of this study are:

- material and fuel consumption for collection of the materials used in the engineered soil mixes,
- transport of materials to the application site, which was assumed to be the Eagle's Nest site near Ely, MN on Minnesota State Highway 169. This site was selected due to its use by Saftner et al. (2022) in previous research.

7.2.5 Excluded Processes

Because this preliminary screening LCA study is cradle-to-gate, use-phase activities and disposal/recycling of the engineered soil mixes at end-of-life are excluded. Any required materials packaging is also excluded from the study. In an LCA, some aspects within the set boundaries are often excluded due to statistical insignificance or irrelevance to the goal and scope. Also, the following impacts were excluded from the scope and boundaries of this study:

- Energy and infrastructure required to apply the engineered soil mixes, since they were considered the same for all mixes,
- Energy required to blend the engineered soil mixes before application since this was considered the same for all mixes,
- Sweeping the roadway clean of any nuisance engineered soil mix that may have spilled during application,
- Human activities (e.g., employee travel to and from work), and
- Services (e.g., the use of purchased marketing, consultancy services, and business travel).

7.2.6 Cut-Off Criteria

Cut-off criteria are often used in LCA practice for the selection of processes or flows to be included in the system boundary; the processes or flows below these cut-offs or thresholds are excluded from the study. Several criteria are used in LCA practice to decide which inputs are to be considered, including mass, energy, and environmental relevance. In the current study, every effort was made to include all the flows associated with the processes studied.

7.2.7 Allocation And Recycling

While conducting an LCA, if the life cycles of more than one product are connected, allocation of the process inputs should be avoided by using the system boundary expansion approach. If allocation cannot be avoided, an allocation method – based on physical causality (mass or energy content, for example) or any other relationship, such as economic value – should be used (ISO 2006a). In this study, allocation was not required.

This study used the cut-off approach method for recycling. According to this approach, the first life of a material bears the environmental burdens of its production (e.g., raw material extraction and processing) and the second life bears the burdens of refurbishment (e.g., collection and refining of scrap). The burdens from waste treatment are taken by the life after which they occur (Frischknecht 2010). Given that *DATASMART* LCI data uses the cut-off approach for recycling, it is considered a reasonable default.

7.3 IMPACT ASSESSMENT METHOD

Impact assessment methods are used to convert LCI data (environmental emissions and raw material extractions) into a set of environmental impacts. ISO 14044 does not dictate which impact assessment method to use for a comparative assertion; however, the chosen method needs to be internationally accepted if the results are intended to be used to support a comparative assertion disclosed to the public.

The impact assessment method used for this study was the *LTS v1.02* method, which combines the *ReCiPe 2016 Endpoint (H) v1.05* method's three endpoint categories (human health, ecosystems, resources) with the cumulative energy demand (CED) *v1.11* (Frischknecht et al. 2007), climate change IPCC 2013 GWP 100a *v1.03* (IPCC 2013), and water use (Huijbregts et al. 2017) impact categories. These six categories are of interest and readily understandable to readers of LCA reports. The *LTS 2019 v1.02* impact assessment method is summarized in Table 7.1.

ReCiPe is one of the most recent and updated impact assessment methods available to LCA practitioners. The method addresses several environmental concerns at the midpoint level and then aggregates the midpoints into a set of three endpoint categories. Endpoint characterization models the impact on Areas of Protection (i.e., on human health, ecosystems, and resources). Therefore, the endpoint is a measure of the damage – at the end of the cause-effect chain – caused by a stressor in terms of human life-years lost and the years lived disabled, species disappeared, and resources lost.

Table 7.1. LTS v1.02 impact assessment method (LTS 2019).

Impact Category	Method	Unit
Human Health	*ReCiPe 2016 Endpoint (H) v1.05*	DALY
Ecosystems	*ReCiPe 2016 Endpoint (H) v1.05*	species* yr
Resources	*ReCiPe 2016 Endpoint (H) v1.05*	$/kg
Cumulative Energy Demand	*CED v1.11*	MJ
Climate Change	*IPCC 2013 GWP 100a v1.03*	kg CO_2 eq.
Water Use	*ReCiPe 2016 Endpoint (H) v1.05*	m^3

The cumulative energy demand (CED) of a product is the direct and indirect energy used throughout the life cycle, including the energy consumed during materials extraction, manufacturing, and disposal. The CED method considers both renewable and non-renewable energy and direct and indirect energy consumption.

The *IPCC 2013* method for assessing the Global Warming Potential (GWP) (i.e., climate change) was developed by the Intergovernmental Panel on Climate Change (IPCC). It is one of the most widely used methods to estimate the climate change potential of global warming gases in LCA studies. Global warming factors have been developed for 20-, 100-, and 500-year time horizons to address the GWP of emissions in both the short and long term. This study uses climate change factors for the 100-year time horizon.

7.3.1 Endpoint Categories

- **Human Health -** In this category, the damage analysis links the six midpoint categories (climate change, human toxicity, photochemical oxidant formation, particulate matter formation, ionizing radiation, and ozone depletion) to the Disability Adjusted Life Years (DALYs). The DALY tool is primarily a disability weighting scale of 0 – 1, where 0 represents perfect health and 1 represents death.
- **Ecosystems -** The damage to ecosystems is measured by calculating the species that disappear in each period and area. The unit of damage assessment is species lost in one year (species*yr). The midpoint impact potentials that apply to ecosystem quality are climate change, terrestrial acidification, freshwater eutrophication, ecotoxicity, agricultural land occupation, urban land occupation, and natural land transformation.
- The two midpoint categories contributing to the resources category are Fossil Depletion and Metal Depletion. The quantification of the damage is based on the marginal increase in cost due to the extraction of resources, measured as dollars per kilogram ($/kg).

7.3.2 Midpoint Categories

- **Cumulative Energy Demand -** This category includes non-renewable (fossil and nuclear) and renewable (biomass, water, solar, wind, and geothermal) energy sources. Characterization factors are based on the upper (or higher) heating value and are expressed as equivalent megajoules (MJ).
- **Climate Change -** Several gaseous emissions cause global warming, including carbon dioxide (CO_2), methane (CH_4), nitrous oxides (NO_x), and fluorinated gases. This category combines the effect of the periods that the various greenhouse gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. The GWP is measured as kg equivalents of CO_2 (i.e., the relative global GWP of a gas compared to CO_2). The IPCC model with a 100-year time horizon is used for characterization. The uptake of CO_2 from the air (i.e., sequestration of CO_2 by plants) and the subsequent emission of biogenic CO_2 (from the burning of biomass) is not included.
- **Water Use -** Water use is based on water consumption, which is the use of water in such a way that the water is evaporated, incorporated into products, transferred to other watersheds, or disposed into the sea (Falkenmark et al. 2004). Water that has been consumed, therefore, is no longer available in the watershed of origin for humans or

ecosystems. The water use category does not include any water required for RCA dust control or for sweeping materials before and during collection.

7.4 LIMITATIONS OF THE STUDY

This is a cradle-to-gate screening LCA using mainly secondary data. To make external claims per ISO 14044, this study would need to be expanded to include: (1) Cradle-to-grave system boundary (including distribution transport, use, and end-of-life phases); (2) Primary data for key processes; (3) Additional sensitivity analyses; (4) Data quality requirements and indicators; and (5) Critical review.

7.5 LIMITATIONS OF LCA METHODOLOGY

LCA's ability to consider the entire life cycle of a product makes it an attractive tool for the assessment of potential environmental impacts. Nevertheless, like other environmental management analysis tools, LCA has several limitations.

First, with the current availability of data, it is challenging to follow the entire supply chain associated with a product's life in a company- or manufacturer-specific way. Instead, almost all processes within the supply chains are modeled using average industry data with varying amounts of specificity (e.g., data on a more-or-less specific technology or region). This makes it difficult to accurately determine how well the unit process data represents the actual factors in the product's life cycle. It also makes it difficult to know in which region the processes are found.

Second, LCA is based on a linear extrapolation of emissions with the assumption that all the emissions contribute to an environmental effect. This is contrary to threshold-driven environmental and toxicological mechanisms. Thus, while linear extrapolation is a reasonable approach for more global and regional impact categories such as GWP and Acidification, it may not accurately represent the actual on-the-ground human- and ecotoxicity-related impacts.

Finally, even if the study had been critically reviewed, it should be noted that, as for any LCA, the impact assessment results are relative expressions and do not predict impacts on category midpoints, exceeding thresholds, or risks. It should also be noted that even though LCA covers a wide range of environmental impact categories, some types of environmental impacts (e.g., noise, social, and economic impacts) are typically not included in LCA.

7.6 LIFE CYCLE INVENTORY

The second phase of an LCA is to collect LCI data, which contains the details of the resources flowing into a process and the emissions flowing from a process to air, soil, and water. The LCI for the three engineered soil mixes is described below.

7.6.1 Recycled Concrete Aggregate (RCA) (80%) with Ash Sawdust (20%) Engineered Soil Mix

As previously noted, secondary inventory data was used in this study for most processes, with most of it readily available in the *DATASMART* or *ecoinvent v3.8* (Wernet et al. 2016) databases. The data used in the LCA model for one ton of RCA and ash sawdust-engineered soil mix at an 80:20 ratio is shown in Table 7.2. The following assumptions were made when tabulating this LCI data:

- The RCA and ash sawdust were used burden-free since they are by-products; this is consistent with the cut-off approach method for recycling used in this study.
- The RCA was collected from Northland Constructors in Duluth, MN, and transported 101 miles via truck to the Eagle's Nest application site near Ely, MN. The ash sawdust was transported 96 miles via truck from the Lester River Sawmill in Duluth, MN to the application site near Ely, MN.
- The engineered soil mixes did not require any sifting/screening before application.
- The system boundary included the application of the engineered soil mix through the first flush of rainwater. Emissions to water were based on previous laboratory studies (Saftner et al. 2023). It was assumed that emissions to water scaled linearly from the laboratory trials to full-scale field application of the engineered soil mixes.
- Attempts were made to include per-and polyfluoroalkyl substance (PFAS) emissions to water. If an exact waterborne emission match was unavailable in the LCI databases, attempts were made to find a close/suitable proxy. If a close match was unavailable, the compound was excluded from the LCA model.
- The unit for transport is ton-miles (ton-mi); one ton-mile refers to one ton of freight carried in one mile.

Table 7.2. Life cycle inventory data for 1 ton of recycled concrete aggregate (RCA) (80%) with ash sawdust (20%) engineered soil mix.

Description	LCI Data Source/Notes	Quantity	Unit
Recycled concrete aggregate (RCA)	This study used the cut-off approach to recycling, the environmental burdens of this material are attributed to the original producer	0	ton
Ash sawdust	This study used the cut-off approach to recycling, the environmental burdens of this material are attributed to the original producer	0	ton
Truck transport	Transport, single-unit truck, diesel-powered NREL/US U	100	ton-mi
Cu emission to water	Copper, waterborne emission	0.6718	g
Zn emission to water	Zinc, waterborne emission	0.5198	g
PO_4 emission to water	Phosphate, US, waterborne emission	94.64	g
NO_3 emission to water	Nitrate, US, waterborne emission	5.095	g
Perfluorobutanoic acid (PFBA) emission to water	Perfluorobutanoic acid (PFBA), waterborne emission	0.0195	mg
Perfluoropentanoic acid (PFPeA) emission to water	Pentanoic acid, waterborne emission	0.0144	mg
Perfluorobutane sulfonate (PFBS) emission to water	Perfluorobutane sulfonate (PFBS), waterborne emission	0.0050	mg
Perfluorohexanoic acid (PFHxA) emission to water	Perfluorohexanoic acid (PFHxA), waterborne emission	0.2523	mg
Perfluoropentane sulfonic acid (PFPeS) emission to water	Perfluoropentane, airborne emission	0.4480	mg
Perfluoroheptanoic acid (PFHpA) emission to water	Perfluoroheptanoic acid (PFHpA), waterborne emission	0.0097	mg
Perfluorohexane sulfonate (PFHxS) emission to water	Perfluorohexane sulfonate (PFHxS), waterborne emission	0.0081	mg
Perfluorooctanoic acid (PFOA) emission to water	Perfluorooctanoic acid (PFOA), waterborne emission	0.1509	mg

7.6.2 Recycled Concrete Aggregate (RCA) (80%) with Peat/Biochar (20%) Engineered Soil Mix

The data used in the LCA model for one ton of RCA and peat/biochar engineered soil mix at an 80:20 ratio is shown in Table 7.3. The following assumptions were made when tabulating this LCI data:

- The RCA, peat, and biochar were used burden-free since they were considered a by-product; this is consistent with the cut-off approach method for recycling used in this study. The peat and biochar were mixed in a 40:60 ratio, respectively, by weight.
- The RCA was collected from Northland Constructors in Duluth, MN, and transported 101 miles via truck to the Eagle's Nest application site near Ely, MN. The peat/biochar mixture was produced in Aitkin, MN, and transported 158 miles via truck to the application site near Ely, MN.
- The engineered soil mixes did not require any sifting/screening before application.
- The system boundary included the application of the engineered soil mix through the first flush of rainwater. Emissions to water were based on previous laboratory studies (Saftner et al. 2023). It was assumed that emissions to water scaled linearly from laboratory trials to full-scale field application of the engineered soil mixes.
- Attempts were made to include PFAS emissions to water. If an exact waterborne emission match was unavailable in the LCI databases, attempts were made to find a close/suitable proxy. If a close match was unavailable, the compound was excluded from the LCA model.

7.6.3 Dredge Sediment (80%) with Degritter (20%) Engineered Soil Mix

The data used in the LCA model for one ton of dredge sediment and degritter-engineered soil mix at an 80:20 ratio is shown in Table 7.4. The following assumptions were made when tabulating this LCI data:

- The dredge sediment and degritter were used burden-free since they are by-products; this is consistent with the cut-off approach method for recycling used in this study.
- The dredged sediment was collected from the Wabasha Gravel Pit in Wabasha, MN, and transported 317 miles via truck to the Eagle's Nest application site near Ely, MN. The degritter was collected at the Sappi mill in Cloquet, MN, and transported 109 miles via truck to the application site near Ely, MN.
- The engineered soil mixes did not require any sifting/screening before application.
- The system boundary included the application of the engineered soil mix through the first flush of rainwater. Emissions to water were based on previous laboratory studies (Saftner et al. 2023). It was assumed that emissions to water scaled linearly from laboratory trials to full-scale field application of the engineered soil mixes.
- Attempts were made to include PFAS emissions to water. If an exact waterborne emission match was unavailable in the LCI databases, attempts were made to find a close/suitable proxy. If a close match was unavailable, the compound was excluded from the LCA model.

Table 7.3. Life cycle inventory data for 1 ton of recycled concrete aggregate (RCA) (80%) with peat/biochar (20%) engineered soil mix.

Description	LCI Data Source/Notes	Quantity	Unit
Recycled concrete aggregate (RCA), Biochar, and Peat	This study used the cut-off approach to recycling, the environmental burdens of this material are attributed to the original producer	0	ton
Truck transport	Transport, single-unit truck, diesel-powered NREL/US U	112	ton-mi
Cu emission to water	Copper, waterborne emission	0.6133	g
Zn emission to water	Zinc, waterborne emission	0.3764	g
PO_4 emission to water	Phosphate, US, waterborne emission	0.0319	g
NO_3 emission to water	Nitrate, US, waterborne emission	30.33	g
Perfluorobutanoic acid (PFBA) emission to water	Perfluorobutanoic acid (PFBA), waterborne emission	0.0328	mg
Perfluoropentanoic acid (PFPeA) emission to water	Pentanoic acid, waterborne emission	0.0386	mg
Perfluorobutane sulfonate (PFBS) emission to water	Perfluorobutane sulfonate (PFBS), waterborne emission	0.0225	mg
Perfluorohexanoic acid (PFHxA) emission to water	Perfluorohexanoic acid (PFHxA), waterborne emission	0.2602	mg
Perfluoropentane sulfonic acid (PFPeS) emission to water	Perfluoropentane, airborne emission	0.5967	mg
Perfluoroheptanoic acid (PFHpA) emission to water	Perfluoroheptanoic acid (PFHpA), waterborne emission	0.0188	mg
Perfluorohexane sulfonate (PFHxS) emission to water	Perfluorohexane sulfonate (PFHxS), waterborne emission	0.0565	mg
Perfluorooctanoic acid (PFOA) emission to water	Perfluorooctanoic acid (PFOA), waterborne emission	0.1640	mg

Table 7.4. Life cycle inventory data for 1 ton of dredge sediment (80%) with degritter (20%) engineered soil mix.

Description	LCI Data Source/Notes	Quantity	Unit
Dredge sediment and degritter	This study used the cut-off approach to recycling, the environmental burdens of this material are attributed to the original producer	0	ton
Truck transport	Transport, single-unit truck, diesel-powered NREL/US U	275	ton-mi
Pb emission to water	Lead, waterborne emission	0.0637	g
Cu emission to water	Copper, waterborne emission	0.8922	g
Zn emission to water	Zinc, waterborne emission	0.6378	g
PO_4 emission to water	Phosphate, US, waterborne emission	5.795	g
NO_3 emission to water	Nitrate, US, waterborne emission	0.3028	g
Perfluorobutanoic acid (PFBA) emission to water	Perfluorobutanoic acid (PFBA), waterborne emission	0.0162	mg
Perfluorohexanoic acid (PFHxA) emission to water	Perfluorohexanoic acid (PFHxA), waterborne emission	0.0257	mg
Perfluoroheptanoic acid (PFHpA) emission to water	Perfluoroheptanoic acid (PFHpA), waterborne emission	0.0081	mg
Perfluorooctanoic acid (PFOA) emission to water	Perfluorooctanoic acid (PFOA), waterborne emission	0.0230	mg
Perflurorheptane sulfonic acid (PFHpS) emission to water	Perfluoroheptane, airborne emission	0.0072	mg
Perfluorooctane sulfonic acid (PFOS) emission to water	Perfluorooctanesulfonic acid (PFOS), waterborne emission	0.0253	mg
Perfluorodecanoic acid (PFDA) emission to water	Perfluorodecanoic acid (PFDA), waterborne emission	4.371	mg

7.7 DATA QUALITY

The quality of the data used in this preliminary LCA is considered to be reasonably accurate and representative of the processes modeled. However, Data Quality Requirements and Indicators (DQI) have not been assigned to this study. (This includes evaluation of data reliability, completeness, geographical correlations, further technological correlation, and sample size using the Pedigree Matrix (Weidema and Wesnaes 1996, Frischknecht et al. 2004).)

7.8 RESULTS OF LIFE CYCLE IMPACT ASSESSMENT

7.8.1 Contribution Analysis

The contribution analysis helps to identify the environmental "hot spots," which are the processes that contribute disproportionately to the overall life cycle (cradle-to-gate for this study) impacts of the engineered soil mixes. The identification of "hot spots" provides a deeper understanding of what is driving the environmental performance of the system and allows for the identification of opportunities for process improvement. For each of the three engineered soil mixes, transportation contributed nearly 100% of the impacts in each impact category; this is largely because each of the feedstocks used for the soil mixes was considered a by-product and was therefore available burden-free, which is consistent with the cut-off approach method for recycling used in this study.

7.8.2 Comparative Analysis

Figure 7.1 presents a comparative analysis between 1 ton of each of the three engineered soil mixes. As shown, the engineered soil mix consisting of dredge sediment (80) with degritter (20%) had substantially higher impacts in each impact category. While the RCA (80%) with ash sawdust (20%) engineered soil mix had the lowest impacts in each category, they were very similar to those of the RCA (80%) with peat/biochar (20%) engineered soil mix. Differences between these two mixes varied from a low of 4.32% for human health to 4.55% for cumulative energy demand. The comparative analysis data is also presented in Table 7.5.

To provide greater insight, Figure 7.2 presents the results of the impact assessment assuming the transportation of all materials from the site of their generation to the application site was 100 miles. This analysis can be useful if the transport distance of the materials is unknown. As shown, all engineered soil mixes have essentially the same impacts, with the RCA (80%) with peat/biochar mix (20%) engineered soil mix having slightly fewer impacts in the human health impact category. The minor differences between the engineered soil mixes in the human health impact category were driven primarily by emissions of zinc to water.

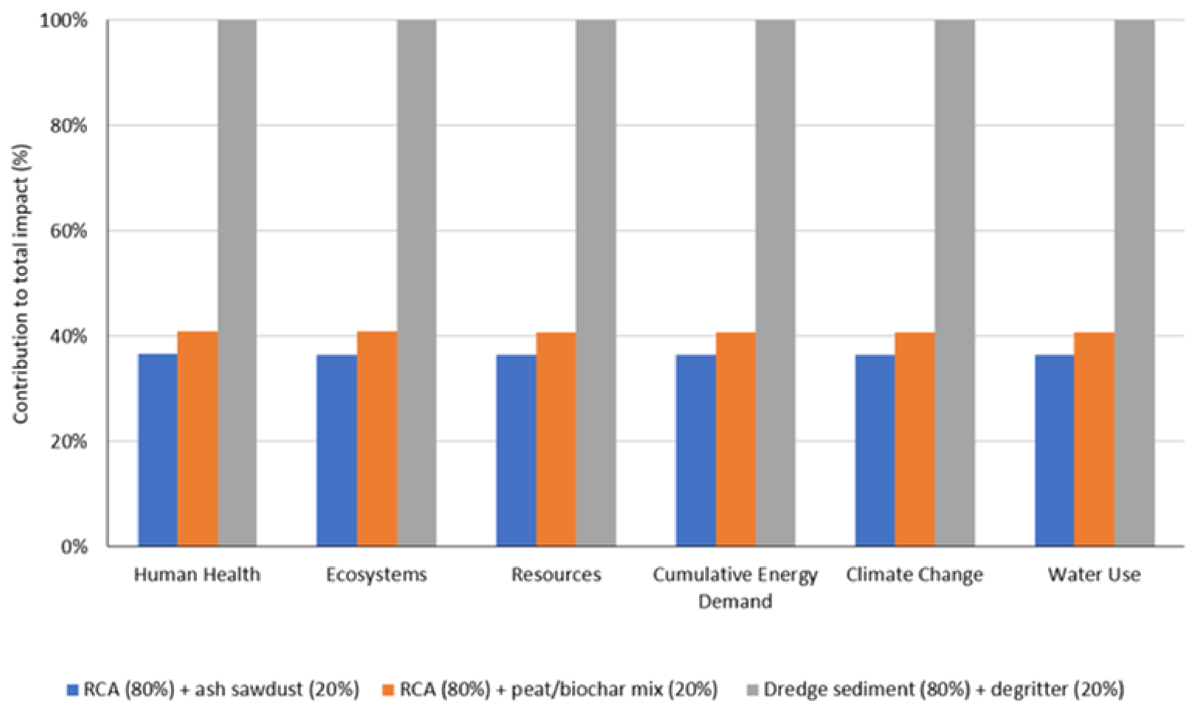

Figure 7.1. Comparative analysis of impact assessment results per ton of engineered soil mix.

To provide even greater insight into the impacts of the engineered soil mixes themselves, a comparison was made between the soil mixes with no transportation inputs. The results are presented in Figure 7.3. As shown, the RCA (80%) with peat/biochar mix (20%) engineered soil mix had the fewest impacts in each category, with 22% and 14% fewer impacts than the RCA (80%) with ash sawdust (20%) engineered soil mix in the human health and ecosystems impact categories, respectively. The dredge sediment (80%) with degritter (20%) engineered soil mix had the highest impacts in each impact category. The differences between the engineered soil mixes in the human health impact category were driven primarily by the copper, lead, and nitrate emissions to water, while the differences in the Ecosystems impact category were driven primarily by the copper, lead, nitrate, and PFPeA emissions to water. There were no impacts in the resources, cumulative energy demand, climate change, and water use impact categories since no transportation was required and all materials required to manufacture the engineered soil mixes were available burden-free.

Table 7.5. Comparative analysis of impact assessment results per ton of engineered soil mix. (*Disability Adjusted Life Years)

Impact Category	Unit	RCA (80%) + ash sawdust (20%)	RCA (80%) + peat/biochar mix (20%)	Dredge sediment (80%) + degritter (20%)
Human Health	DALY*	5.35E-5	5.98E-5	1.46E-4
Ecosystems	species *yr	1.40E-7	1.57E-7	3.85E-7
Resources	$/kg	3.82	4.29	10.5
Cumulative Energy Demand	MJ	400	450	1.10E3
Climate Change	kg CO_2 eq.	300	33.7	82.6
Water Use	m^3	3.41E-2	3.83E-2	9.38E-2

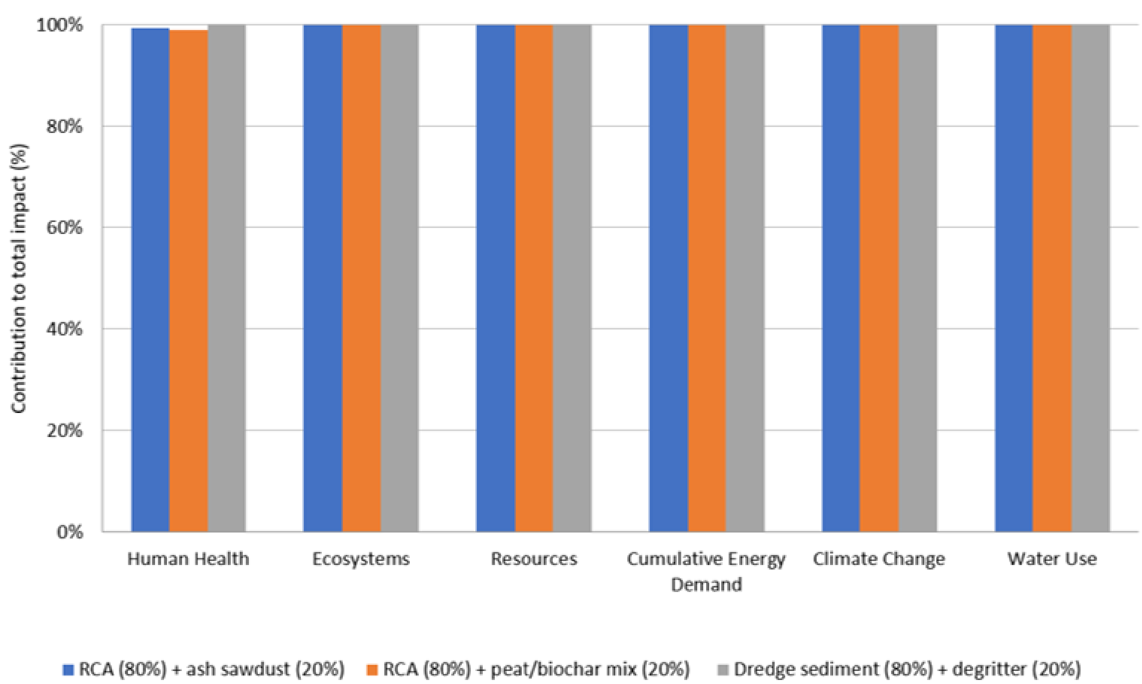

Figure 7.2. Comparative analysis of impact assessment results per ton of engineered soil mix with 100 miles of transportation distance.

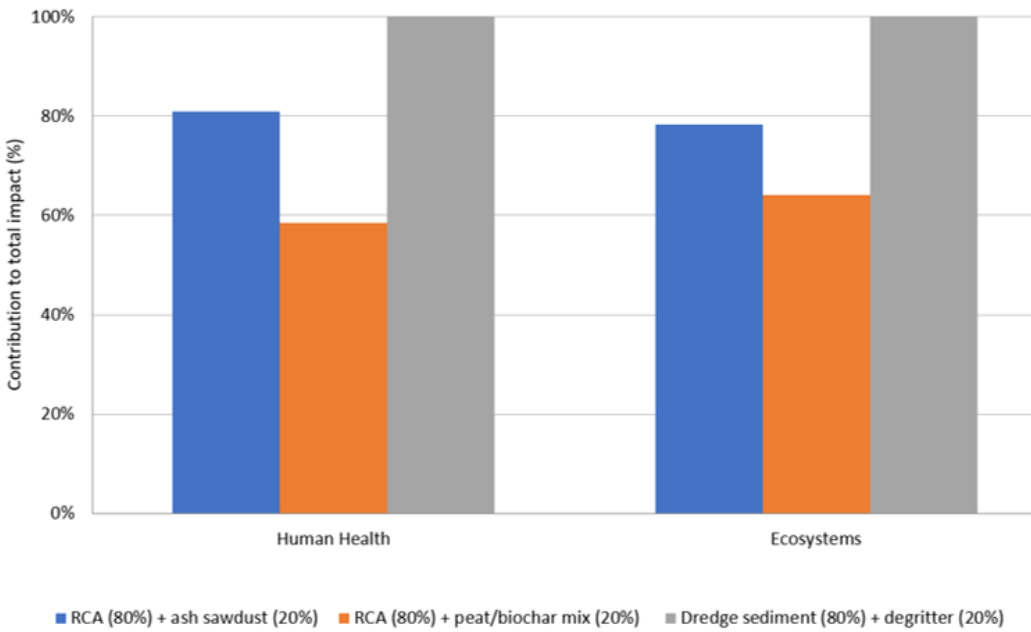

Figure 7.3. Comparative analysis of impact assessment results per ton of engineered soil mix with no transportation.

While it is not possible to calculate an "optimal" distance for transporting the engineered soil mixes from their collection sites to the Eagle's Nest site, a sensitivity analysis revealed that, if the dredge sediment (80%) with degritter (20%) engineered soil mix had its transportation distance reduced from the baseline of 275 miles to 110 miles, the overall potential environmental impacts of this mix would be approximately the same as the RCA (80%) with peat/biochar mix (20%) engineered soil mix. If the transport distance for the dredge sediment (80%) with degritter (20%) engineered soil mix was reduced from the baseline of 275 miles to 105 miles, the potential environmental impacts in all impact categories would be within 5% of the RCA (80%) with ash sawdust (20%) engineered soil mix. This sensitivity analysis reveals how transportation distance has a large impact on the overall potential environmental impacts.

A comparison of the potential environmental impacts of the three engineered soil mixes to traditional materials, such as soil, would need to consider whether the soil needed to be prepared or processed in any way to be used at the Eagle's Nest site; the mass and density of the soil; and the Pb, Cu, Zn, PO_4, NO_3, and PFAS emissions from the soil. However, this study did not evaluate these processing needs or soil emissions, so a direct comparison cannot be made.

7.8.3 Comparative Analysis: Co_2 Emissions to Air

Figure 7.4 presents the amount of CO_2 emitted to the air per ton of engineered soil mix. CO2 emissions include both fossil and biogenic emissions, as well as those from land transformation. As shown, the dredge sediment (80%) with degritter (20%) engineered soil mix had 77 kg of CO_2 emissions per ton, while the RCA (80%) with ash sawdust (20%) and RCA (80%) with peat/biochar mix (20%) engineered soil mixes had 28 kg and 32 kg of CO_2 emissions per ton, respectively. Most CO_2 emissions for each engineered soil mix can be attributed to the transportation required to ship the materials from their respective collection sites to the application site.

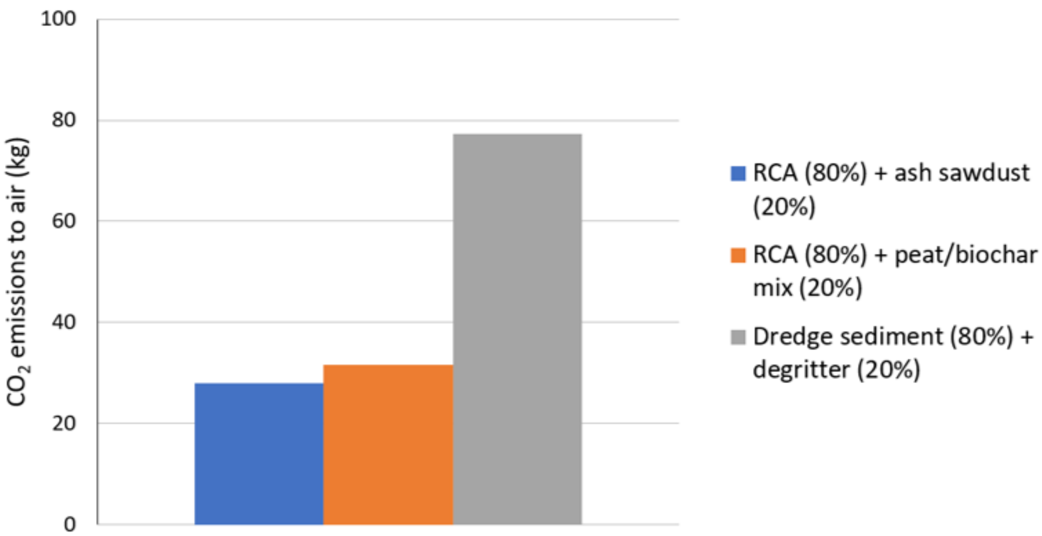

Figure 7.4. CO2 emissions to air per ton of engineered soil mix.

7.9 CONCLUSIONS

The objective of this study was to understand the potential environmental impacts of the three performing engineered soil mixes on a cradle-to-gate basis. A contribution analysis of the three engineered soil mixes showed that transportation contributed nearly 100% of the impacts in each impact category; this is because each of the feedstocks was considered a by-product and was therefore available burden-free. A comparative analysis revealed that the dredge sediment (80%) with degritter (20%) engineered soil mix had substantially higher impacts than the two other engineered soil mixes in each impact category; it also had the largest CO_2 emissions to air. While the RCA (80%) with ash sawdust (20%) engineered soil mix had the lowest impacts in each category, it was very similar to those of the RCA (80%) with peat/biochar (20%) engineered soil mix. Differences between these two mixes varied from a low of 4.32% for human health to 4.55% for cumulative energy demand. Future research could consider how local or regional soil or similar materials perform regarding emissions of contaminants compared to the three engineered soil mixes studied, as well as costs for any required soil processing and transport to the installation site.

CHAPTER 8: CONCLUSIONS

8.1 INTRODUCTION

This study highlights the significant potential of utilizing engineered mixed by-products as biofiltration media. The primary application in this research has been bioslopes and bioswales; however, wider application to related areas is possible. The findings indicate that a combination of organic and inorganic materials effectively captures stormwater runoff, removes pollutants, and promotes the growth of native plants. Subsequent sections elaborate on these conclusions, drawn from laboratory tests and onsite monitoring of field plots, and present a guideline developed for state engineers to enhance stormwater management strategies.

8.2 CIVIL ENGINEERING CONCLUSIONS

The primary design consideration in civil engineering for this project was the infiltration rate. To assess the worst-case scenario, saturated hydraulic conductivity was the key parameter used to evaluate materials and their combinations, building on findings from previous studies by Johnson et al. (2017), and Saftner et al. (2019, 2022). Laboratory tests on by-products revealed that hydraulic conductivity was determined by the finest material in the mix. Typically, organic materials exhibited high hydraulic conductivities, and generally, coarser materials demonstrated higher conductivities than finer ones. The hydraulic conductivity values of the engineered mixes were intermediate, influenced predominantly by the material with the lowest conductivity in the mix.

From 2017 to 2024, monitoring of two field plots assessing the performance of the engineered mixes confirmed that the media effectively captured the first inch of excess precipitation directed toward the biofiltration system.

8.3 ENVIRONMENTAL ENGINEERING CONCLUSIONS

Based on the chemical characterization, all nine waste materials studied are considered safe for use as soil amendments, with negligible levels of RCRA metals, PAHs, and PCBs detected. The release of metals, nitrate, phosphate, and PFAS was generally minimal. However, it's important to consider the pH properties of these materials to ensure neutral water treatment upon application. Additionally, these materials exhibit capacities to remove metals, nitrate, and phosphate, with efficiency varying accordingly. The difference suggests lab testing is necessary for any new materials before the application.

Field application of a mixture comprising 20% organic and 80% inorganic materials resulted in low concentrations of copper, zinc, and phosphate in the filtered water. Moreover, temporal declining trends in phosphate concentrations observed in previously established field plots emphasize the importance of long-term monitoring to elucidate potential changes over time.

8.4 BIOLOGICAL CONCLUSIONS

Greenhouse testing revealed comparable plant heights and biomass among materials with neutral or slightly acidic properties, whereas growth was notably low for alkaline media. Interestingly, a soil mixture comprising 20% organic matter with 80% inorganic components supported plant growth in the greenhouse very well. However, in experimental plots using the same soil mixture, grass growth was scarcely observed, likely attributed to the extended dry season experienced in 2023. It is recommended to conduct long-term monitoring to assess whether unfertilized soil alone can sustain continuous plant growth. Additionally, this monitoring can help determine the appropriate amount and frequency of fertilization if any supplemental fertilizer is applied.

8.5 LIFE-CYCLE ASSESSMENT CONCLUSIONS

The preliminary LCA revealed that transportation contributed nearly 100% of the impacts in each impact category. A comparative analysis revealed that the dredge sediment (80%) with degritter (20%) engineered soil mix had substantially higher impacts than the RCA (80%) with ash sawdust (20%) and RCA (80%) with peat/biochar (20%) engineered soil mixes; it also had the largest CO_2 emissions to air. While the RCA (80%) with ash sawdust (20%) engineered soil mix had the lowest impacts in each category, it was very similar to those of the RCA (80%) with peat/biochar (20%) engineered soil mix. Differences between these two mixes varied from a low of 4.32% for human health to 4.55% for cumulative energy demand. Future research could consider how local or regional soil or similar materials perform regarding emissions of contaminants compared to the three engineered soil mixes studied, as well as costs for any required soil processing and transport to the installation site.

8.6 DESIGN GUIDE

The guide developed under this project promotes the use of locally sourced waste materials and by-products as substitutes for sand and/or compost while still adhering to regulatory standards. The recommended practices are designed to be standard, common, and repeatable, minimizing implementation barriers. Engineered soil mixtures offer benefits such as sustainable material reuse, reduced costs for sand and compost, lower transportation expenses, and diminished environmental impacts associated with material transport. This guide is a component of a MnDOT research project detailed in MnDOT Contract No. 1036342, Work Order No. 53, titled *Re-use of Minnesota Waste in Sustainably Designed Soils – Part 2.* The full report provides comprehensive details and background, and it is advised to reference this report when using the guide.

REFERENCES

Arias M.E., Gonzalez-Perez, J.A., Gonzalez-Vila, F.J., and Ball, A.S. (2005). Soil Health — A New Challenge for Microbiologists and Chemists. *International Microbiology.* Retrieved from pubmed.ncbi.nlm.nih.gov/15906257/

Cai, M., Patelke, M., & Saftner, D. (2021). *Continued Monitoring of Stormwater Effluents from Filter Media in Two Bioslope Sites* (Report No. MN/RC 2021-15). St. Paul, MN: Minnesota Department of Transportation.

Center for Watershed Protection. (2020, Feb. 13). Trees and Stormwater Runoff. Retrieved from cwp.org/reducing-stormwater-runoff/#:~:text=Stormwater%20runoff%20is%20the%20number,falling%20over%20a%20forested%20area

EPA. (1995, Aug.). *Controlling Nonpoint Source Runoff Pollution from Roads, Highways and Bridges*. Retrieved from archive.epa.gov/owow/NPS/roads.html#:~:text=As%20it%20flows%20over%20these,pet%20waste%2C%20and%20other%20litter

Daniels, W.L., Whittecar, G.R., and Carter, C.H. (2007). Conversion of Potomac River Dredge Sediments to Productive Agricultural Soils. *Journal American Society of Mining and Reclamation*, *2007*(1), 183–199. doi:10.21000/jasmr07010183

Darmody, R. G., & Marlin, J. C. (2008). Illinois River Dredged Sediment: Characterization and Utility for Brownfield Reclamation. *Journal American Society of Mining and Reclamation*, *2008*(1), 253–270. doi:10.21000/jasmr08010253

Dauce, P. D., de Castro, G.B., Lima, M.M.F., and Lima, R.. (2019). Characterization and Magnetic Concentration of Iron Ore Tailings. *Journal of Materials Research and Technology*. Retrieved from www.sciencedirect.com/science/article/pii/S2238785418300760

Environmental Protection Agency (EPA). (2023). EPA Wasted Food Scale. Retrieved from www.epa.gov/sustainable-management-food/reducing-impact-wasted-food-feeding-soil-and-composting#:~:text=Like%20yard%20waste%2C%20food%20waste,crops%2C%20and%20 improve%20water%20 quality

EPA. (1995). *Trees and Stormwater Runoff.* Washington, DC: Environmental Protection Agency. archive.epa.gov/owow/NPS/roads.html

Expert Environmental Consulting. (2018, Jan. 21). *What Is Stormwater Management and Why Is It Important?* Expert Environmental Consulting. Retrieved from eecenvironmental.com/what-is-stormwater-management/

Falkenmark, M., & Rockstrom, J. (2004). Balancing Water for Humans and Nature. In *The New Approach in Ecohydrology*. London: Earthscan.

Frischknecht, R., Althaus H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., … & Spielmann, M. 2004. *Overview and Methodology* (Final report Ecoinvent v2.0 No. 1). Dübendorf, Switzerland: Swiss Centre for Life Cycle Inventories.

Frischknecht, R. (2010). LCI Modeling Approaches Applied to Recycling of Materials in View of Environmental Sustainability, Risk Perception, and Eco-Efficiency. *International Journal of Life Cycle Assessment*, *15*, 666–671.

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., … & Nemecek, T. (2007). *Implementation of Life Cycle Impact Assessment Methods* (ecoinvent report No. 3, v2.0). Dübendorf, Switzerland: Swiss Centre for Life Cycle Inventories.

Gaffield, S. J., Goo, R.L., Richards, L.A., and Jackson, R.J. (2003, Sept.) Public Health Effects of Inadequately Managed Stormwater Runoff. *American Journal of Public Health*. Retrieved from www.ncbi.nlm.nih.gov/pmc/articles/PMC1448005/

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., and van Zelm, R. (2017). ReCiPe2016: A Harmonized Life-Cycle Impact Assessment Method at Midpoint and Endpoint Level. *Int J Life Cycle Assess*, *22,* 138.

Intergovernmental Panel on Climate Change. (IPCC). (2013). *IPCC Fifth Assessment Report. The Physical Science Basis*. Cambridge University Press, Cambridge, United Kingdom.

International Organization for Standardization (ISO) 14040. (2006). *Environmental Management—Life-Cycle Assessment—Principles and Framework*. Location: Geneva.

Johnson, K., Cai, M., Patelke, M., Saftner, D., & Swanson, J. (2017). *Comparing Properties of Water Absorbing/Filtering Media for Bioslope/Bioswale Design* (Report No. MN/RC 2017-46). St. Paul, MN: Minnesota Department of Transportation.

Jungbluth N., Nemecek, T., Rebitzer, G., & Spielmann, M. (2004). *Overview and Methodology* (Final report Ecoinvent v2.0 No. 1). Dübendorf, Switzerland: Swiss Centre for Life Cycle Inventories.

Koropchak, S. C., Daniels, W.L., Wick, A., Whittecar, G.R., and Haus, N. (2016). Beneficial Use of Dredge Materials for Soil Reconstruction and Development of Dredge Screening Protocols. *Journal of Environmental Quality*, 45(1), 62–73. doi:10.2134/jeq2014.12.0529

L., Chethan, et al. (2022). Expansive Soil Stabilization Using Iron Ore Tailings. *International Journal of Advanced Research*, *10*(07), 80–89. doi:10.21474/ijar01/15006

Lal, R. (2006). Enhancing Crop Yields in the Developing Countries through Restoration of the Soil Organic Carbon Pool in Agricultural Lands. *Land Degradation & Development*, 17(2), 197–209. doi:10.1002/ldr.696

Lal, R. (2016). Soil Health and Carbon Management. *Food and Energy Security*, 5(4), 212–222. doi:10.1002/fes3.96

LTS. (2019). *LTS 2019 v1.02* Impact Assessment Method. Location: Meridian, MS.

LTS. (2020). *DATASMART* LCI Package. Retrieved from

MPCA. (2013). *Understanding Solid Waste.* St. Paul, MN: Minnesota Pollution Control Agency. www.pca.state.mn.us/air-water-land-climate/understanding-solid-waste.

Ninnes, S., Tolu, J., Meyer-Jacob, C., Mighall, T.M., and Bindler, R. (2017). Investigating Molecular Changes in Organic Matter Composition in Two Holocene Lake-Sediment Records from Central Sweden Using Pyrolysis-GC/MS. *Journal of Geophysical Research: Biogeosciences*, 122(6), 1423–1438. doi:10.1002/2016jg003715

Patelke, M., Cai, M., and Saftner, D. (2021). *Continued Monitoring of Stormwater Effluents from Filter Media in Two Bioslope Sites.* Minneapolis: Center for Transportation. www.cts.umn.edu/publications/report/continued-monitoring-of-stormwater-effluents-from-filter-media-in-two-bioslope-sites

PRé. (2016). *SimaPro v9.5.0.0* LCA software. Amersfoort, The Netherlands: PRé Consultants bv.

Saftner, D., Amoateng, G., Cai, M., Aro, M., & Wisniewski, D. (2023). *Re-Use of Minnesota Waste in Sustainably Designed Soils – Part 2* (MnDOT Contract No 1036342, Work Order 53, Task 4 Deliverable). St. Paul, MN: Minnesota Department of Transportation.

Saftner, D., Cai, M., & Whitcomb, A. (2022). *Re-Use of Regional Waste in Sustainably Designed Soils*. (Research Project, Final Report no. MN 2022-10). St. Paul, MN: Minnesota Department of Transportation.

Saftner, D., Carranza-Torres, C., & Nelson, M. (2017). *Slope Stabilization Guide for Minnesota Local Government Engineers* (Report No. MN/RC 2017-17G). St. Paul, MN: Minnesota Department of Transportation.

Saftner, D., Cruz, C., Cai, M., Johnson, K., & Patelke, M. (2019). *Development and Regionalization of Bioslopes and Bioswales* (Report No. MN/RC 2019-31). St. Paul, MN: Minnesota Department of Transportation.

Saftner, D., Carranza-Torres, C., & Nelson, M. (2017a). *Slope Stabilization and Repair Solutions for Minnesota Local Government Engineers* (Report No. MN/RC 2017-17). St. Paul, MN: Minnesota Department of Transportation.

Saftner, D., & Cei, M.. (2022). *Re-Use of Regional Waste in Sustainably Designed Soils.* Minneapolis: Center for Transportation Studies. www.cts.umn.edu/research/project/re-use-of-regional-waste-in-sustainably-designed-soils.

Scharenbroch, B.C., and Watson, G.W.. (2014). *Wood Chips and Compost Improve Soil Quality and Increase Growth of Acer rubrum and Betula nigra in Compacted Urban Soil.* Atlanta, Georgia: International Society of Arboriculture. www.treefund.org/wp-content/uploads/2016/12/ScharenbrochWatson_2014_auf.pdf

Standard Operation Manual—Oregon. (2018). *Standard Operation Manual—Water Quality Filter Strips and Bio-Slopes*. Retrieved from www.oregon.gov/ODOT/GeoEnvironmental/Docs_Hydraulics/SOM_FilterStrip_Bioslope.pdf

Superior Ground Cover. (2020, Jan. 2). Crushed Concrete and Concrete Aggregate 101. Superior Groundcover*. Retrieved from* www.superiorgroundcover.com/crushed-concrete-101/

Tang, C., Li, K., Ni, W., and Fan, D.. (2019). *Recovering Iron from Iron Ore Tailings and Preparing Concrete Composite Admixtures*. Multidisciplinary Digital Publishing Institute. Retrieved from www.mdpi.com/2075-163X/9/4/232/htm#:~:text=Introduction-,Iron%20ore%20tailings%20(IOTs)%20are%20a%20form%20of%20solid%20waste,output%20and%20low%20utilization%20ratio

Water Quality Program. (1992). Ecology Publications and Forms. *1992 Stormwater Management Manual for the Puget Sound Basin* (Technical Manual). Retrieved from apps.ecology.wa.gov/publications/summarypages/9175.html

Weidema, B., & Wesnaes, M. S. (1996). Data Quality Management for LCI. *Journal of Cleaner Production*, 4(3-4), 176–174.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The Ecoinvent Database Version 3 (part I): Overview and Methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218-123

APPENDIX A: DESIGN GUIDE

1 INTRODUCTION

This project recommends designing engineered soil mixtures from locally available waste materials and by-products to meet stormwater management regulations. As an alternative to retention type systems, current Minnesota Department of Transportation (MnDOT) practice recommends combining sand and compost to capture on-site the first inch of runoff, often called the first flush. Sand or another clean granular material helps provide the water filtering capability, while compost or another organic material helps support plant growth, soil stability, and water retention capabilities.

The following design guide will allow the use of locally available waste materials and/or by-products to replace sand and/or compost while meeting regulatory requirements. The methods recommended in this guide were chosen to be standard, common, and repeatable to decrease obstacles to implementation. Benefits of engineered soil mixtures include the sustainable reuse of materials currently regarded as waste, decreased purchasing costs for sand and compost, reduced transportation costs, and reduced environmental impacts due to material transport.

This guide is based on ***MnDOT research report: MnDOT Contract No. 1036342, Work Order No. 53, Re-use of Minnesota Waste in Sustainably Designed Soils—Part 2.*** The report provides details, background, and complete descriptions and the authors recommend referencing the report when using this guide.

2 ENGINEERED SOIL MIXTURE DESIGN PROCESS OVERVIEW

To ensure compliance with the design guide for stormwater management applications, follow the protocol shown in Figure 1. The first step is to determine the type of stormwater management application and identify potential waste materials or by-products available for the project (Decision #1). If the material meets the suggested life cycle assessment (LCA) requirements described on Decision #2, proceed to the second step, individual material characterization. To be successfully applied in MnDOT stormwater management applications, the material must meet civil engineering, environmental engineering, and plant growth criteria, described in Decisions #3, #4 and #5, respectively. If the individual material meets all three criteria, the engineered soil mixture proposed for field use is tested to ensure that the mixture meets plant growth requirements, described in Decision #6. If the waste material or by-product does not pass the standards, standard MnDOT practice for designing water retention systems is recommended.

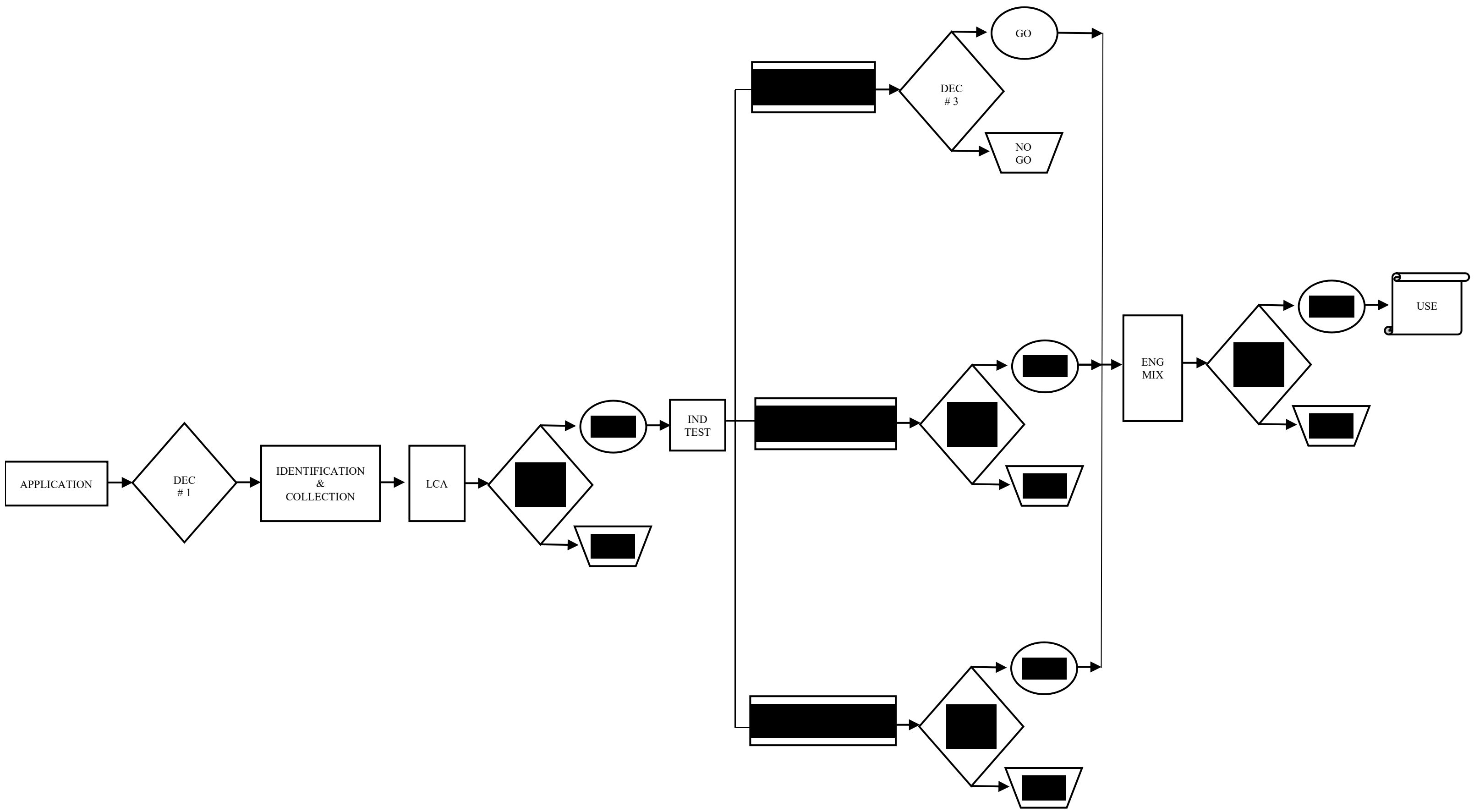

Figure 1. Flow chart showing the process used to determine waste material's or by-product's applicability for use in engineered soil mixtures in stormwater retention systems.

2.1 Decision #1: Stormwater Management Application

To utilize this design guide, state engineers must:

1. Determine the type of stormwater management system to be implemented, such as biofiltration systems, detention ponds, or retention ponds.
2. Classify potential materials such as granular, organic, or topsoil. Table 1 presents typical materials waste products, and by-products investigated through MnDOT research.
3. The engineered mix for biofiltration systems should consist of roughly 60% granular material, 20% organic material, and 20% topsoil.
4. The engineered mix should comprise roughly 60% granular and 40% organic materials for detention or retention ponds.

Table 1. Examples of various material types.

Granular Materials	Organic Materials	Topsoil
Commercial Sand	Peat	Commercial Compost
Dredge Sediments	Muck	
Taconite Tailings	Compost	
Recycled Concrete Aggregate	Tree Bark	
Bottom Ash	Commercial Compost	
Lime Mud	Paper Sludge	
Sand	Peat Scrapping	
Fine Tailings	Peat Screening	
Coarse Tailings	Grit	
Fine-grained Sediments	Street Sweepings	
	Peat/Biochar Mix	
	Versalime	
	Beet Tailings	
	Green Pine Sawdust	
	Green Ash Sawdust	

2.2 Decision #2: Life Cycle Assessment

To determine the potential environmental impacts of the candidate engineered soil mixtures and to identify potential environmental “hot spots” of utilizing them, we suggest completing the following steps:

1. Identify the location of each material that could be used in the engineered soil mixture.
2. Determine if any processing of the materials is required (e.g., screening, sorting, sifting, drying) before being applied in the field. Identify any required inputs (electricity, water) and outputs/wastes if processing is required.
3. Calculate the transportation distance from the materials' collection site to the field application site. Determine the method of transport (e.g., truck, rail, combination).
4. If the material has not been previously screened for contaminants, conduct laboratory studies to determine the materials' contaminant migration to water (e.g., heavy metals, phosphate, PFAS).
5. If more than one material is used to prepare the engineered soil mixture, determine the proper mixing ratio by weight (e.g., 80% of material A + 20% of material B).
6. Establish a function unit for the engineered soil mixture. (The recommended functional unit is one ton of engineered soil mixture.)
7. If possible, conduct a preliminary screening life cycle assessment (LCA) of the engineered soil mixture using ISO 14040 and 14044 guidelines.
8. Use the preliminary LCA results (step 7, above) to guide your selection of candidate materials.

2.3 Decision #3: Civil Engineering Analysis

State engineers should follow these steps to ascertain compliance with MnDOT's minimum infiltration criteria.

1. For each granular, organic, and/or topsoil material with the potential to be used in the engineered soil mixture, perform a gradation test to identify the material's grain size distribution and classify it according to ASTM D6913-04.

2. Using the grain size data, predict the grain size of an engineered soil mixture. The weight retained on a given sieve should be multiplied by the material's percentage in the mix and added to the other material's weight retained on the same sieve after multiplying it by its percentage in the engineered soil mixture. The resulting engineered soil mixture data can be plotted to determine the factors required in the analysis described in Step 3.

3. Predict the engineered soil mixture's hydraulic conductivity using the relationships proposed by Kozeny-Carmen, shown in Equation 1; Moulton, shown in Equation 2; and Beyer, shown in Equation 3. Johnson et al. (2019), Saftner et al. (2024), and Ishaku et al. (2010) showed that Kozeny-Carmen typically slightly overpredicts actual hydraulic conductivity while Moulton and Beyer generally underpredict actual hydraulic conductivity.

$$k=\frac{\gamma}{\mu}\left(\frac{1}{T^2 S_0^2}\right)\left(\frac{e^3}{1+e}\right) \qquad \text{Equation 1}$$

Where k is expressed in centimeters per second, γ is the unit weight of water, μ is the viscosity of water, T is a factor selected based on pore shape, S_0 is the specific surface area of the soil particles, and e is the void ratio.

$$k = \frac{6.214*10^5 (D_{10})^{1.478} (n)^{6.654}}{(P_{200})^{0.597}} \quad \text{Equation 2}$$

Where k is expressed in feet per day, D_{10} is the grain size in mm at which 10% of a sample is passing, n is porosity and P_{200} is the percent passing the #200 sieve.

$$k = \frac{g}{\mu} * 6 * 10^{-4} * \log\left(\frac{500}{U}\right) * (d_{10})^2 \quad \text{Equation 3}$$

Where k is expressed in meters per second, g is gravitational acceleartion, μ is the viscosity of water, U is the coefficient of grain uniformity defined at d_{60} divided by d_{10}, and d_{60} and d_{10} are the diameters in mm of the particles at 60% and 10% passing, respectively.

4. Repeat steps 2 and 3, varying the percent of each granular, organic, and/or topsoil material in the engineered soil mixture, to determine potential engineered soil mixtures with Kozeny-Carmen predicted hydraulic conductivity under and Moulton predicted hydraulic conductivity over the MnDOT minimum hydraulic conductivity of 10^{-3} cm/sec. Any engineered soil mixtures considered using the criteria described on page 3 of this guide should meet minimum hydraulic conductivity.

2.4 Decision #4: Environmental Engineering Analysis

When selecting materials for an engineered soil mixture, the following steps should be followed to ensure the environmentally safe use of materials and optimize stormwater runoff pollutant treatment.

1. Each granular, organic, and/or topsoil material with the potential to be used in the engineered soil mixture must not be listed on the EPA hazardous waste list.
2. Materials not listed as hazardous waste need further testing for ignitability, corrosivity, reactivity, and toxicity using the EPA SW-846 test. The same test is also used to examine the concentrations of eight RCRA (Resource Conservation and Recovery Act) metals: arsenic, barium, cadmium, chromium, lead, mercury, selenium and silver. Any materials characterized as hazardous waste based on the test results are excluded from consideration.
3. For the non-hazardous materials, analyze for Polychlorinated Biphenyls (PCBs), Polycyclic Aromatic Hydrocarbons (PAHs), and Volatile Organic compounds (VOCs) using the EPA SW-846 test by a certified lab, comparing measured values with MPCA soil reference values (SRVs) to ensure contents fall below specified thresholds.
4. Materials selected from Step 3 also need to be characterized for pH, organic matter content, nutrients (nitrogen, phosphorus, potassium), cations (calcium, magnesium), and soluble salts by a

qualified lab. This step aims to gather data on nutrient levels to support plant growth and determine any necessary supplemental mixing.

5. The granular, organic, and/or topsoil material selected from Step 3 is mixed with deionized water to assess potential leaching concentrations, comparing them against standards to prevent chemical leachate pollution of receiving water bodies. The recommended mixing procedure involves combining the solid with deionized water at a raito of 1:10 and mixing for 24 hours. The final chemical concentrations in the liquid determine the amount of chemical released. The mixing ratio and duration can be adjusted based on specfific applications.
6. Materials selected from Step 3 are recommended for mixing with synthesized stormwater following the procedure in Step 5 to evaluate their capacity to remove runoff contaminants, informing decisions on additional materials needed for optimizing stormwater runoff treatment. It is recommended that the work in both Steps 5 & 6 be conducted by a research lab with expertise in batch testing with soil materials.
7. Review study materials against new standards or methods to ensure ongoing compliance and environmental safety.

2.5 Decision #5: Plant Growth Analysis

To effectively select the materials to be applied in the engineered soil mixtures for roadside applications, ensuring that the selected materials can facilitate plant growth is essential. This involves a process conducted through greenhouse testing for individual media, outlined below:

1. Greenhouse Testing for Invasive Species. The first step involves conducting greenhouse tests to examine whether the media contains invasive plant species. This is achieved by regularly watering individual organic and/or topsoil materials placed in pots within a greenhouse for at least two months. The objective is to observe any spontaneous plant growth without the introduction of seeds and to identify if these plants belong to any invasive species lists. If the invasive species are detected, the material must undergo pre-treatment to eliminate them before further application.
2. Collaborate with MnDOT for Seed Selection. Collaborate closely with MnDOT to determine the appropriate grass or plant seeds for roadside application. These seeds will be carefully selected to conduct plant growth tests in the greenhouse.
    a. Plant Growth Assessment. Materials not containing any invasive species are tested with the seeds identified in Step 2 to assess germination rates and subsequent plant growth. Measurements, including germination rates, plant height, and biomass, are taken to evaluate the ability of each material to independently support plant growth. Any materials found to be insufficient in supporting plant growth on their own will require supplementation with additional materials.

2.6 Decision #6: Engineered Soil Mixture Performance Analysis

Following the characterization data of individual granular, organic, and/or topsoil materials identified by Decisions #2, #3, and #4, the materials are carefully chosen to formulate the engineered soil mixture. However, additional plant growth testing is required to assess the mixture's efficacy in supporting plant growth and to ascertain the necessity of additional fertilization for optimal application.

1. Conduct plant growth tests for soil mixtures using the grass or plant species selected by MnDOT. A reference media should also be included for performance evaluation. Mixtures unable to sustain plant growth should be excluded from consideration.
2. Mixtures capable of supporting plant growth but exhibiting lower height or biomass than the reference media require supplementation with fertilizer. The frequency of fertilization depends on the growth condition. The choice of fertilizer can be determined based on the nutrient content identified in Step 4 of Decision #3.

3 ENGINEERED SOIL MIXTURE DESIGN PROCESS EXAMPLE

The following section shows an example of applying the engineered soil mixture process to two waste materials. The granular material is soil dredged from the Duluth-Superior harbor and the organic material is degritter, a material that results from washing incoming logs at the SAPPI Cloquet plant. The intent of this section is to provide an example of how to apply the design steps in practice. If designers conduct all of the tests, the total may be up to six weeks, most of the time resulting from the plant growth tests.

3.1 Decision #1: Stormwater Management Application

1. Determine the type of stormwater management system to be implemented, such as biofiltration systems, detention ponds, or retention ponds.

This example will consider a biofiltration system for use as a bioslope adjacent to a roadway.

2. Classify potential materials such as granular, organic, or topsoil. Table 1 presents typical materials waste products, and by-products investigated through MnDOT research.

The dredge material is a granular material, determined by visual inspection. There is a high percentage of sand and silt sized particles, as well as the lack of organic material's characteristic earthy odor. The degritter is an organic material, determined by the high percentage of bark, twigs, and other organic matter from the log cleaning process.

3. The engineered mix for biofiltration systems should consist of roughly 60% granular material, 20% organic material, and 20% topsoil.
4. The engineered mix should comprise roughly 60% granular and 40% organic materials for detention or retention ponds.

This example will consider a biofiltration system and will initially consider 60% dredge material and 40% degritter. While this example considers the use of only waste materials and by-products, note that 60% dredge material, 20% degritter, and 20% topsoil is another design option.

3.2 Decision #2: Life Cycle Assessment Example

1. Identify the location of each material that could be used in the engineered soil mixture.

Since transportation of the materials from the collection site to the application site is most often the largest contributor to the overall environmental load, consider selecting materials that are the closest to the application site.

2. Determine if any processing of the materials is required (e.g., screening, sorting, sifting, drying) before being applied in the field. Identify any required inputs (electricity, water) and outputs/wastes if processing is required.

These inputs will be added to the screening life cycle assessment (LCA) noted in step 7, below.

3. Calculate the transportation distance from the materials' collection site to the field application site. Determine the method of transport (e.g., truck, rail, combination) .

Transportation distance is critical as transportation of the materials from the collection site to the application site is most often the largest contributor to the overall environmental load; thus, consider selecting materials that are the closest to the application site.

4. If the material has not been previously screened for contaminants, conduct laboratory studies to determine the materials' contaminant migration to water (e.g., heavy metals, phosphate, PFAS) .

The mass of contaminants will be added to the screening life cycle assessment (LCA) noted in step 7, below.

5. If more than one material is used to prepare the engineered soil mixture, determine the proper mixing ratio by weight (e.g., 80% of material A + 20% of material B) .

This example will consider 60% of dredge material and 40% degritter.

6. Establish a function unit for the engineered soil mixture. (The recommended functional unit is one ton of engineered soil mixture.)

While the researchers used one ton of engineered soil mixture in their life cycle assessment (LCA), they recognize that the opportunity to conduct a full LCA in practice is limited. This step is primarily of importance when conducting a formal LCA.

7. If possible, conduct a preliminary screening life cycle assessment (LCA) of the engineered soil mixture using ISO 14040 and 14044 guidelines.

While the researchers conducted a formal LCA, they recognize that this is less common in standard practice. If able to conduct an LCA, it is recommended to use LCA modeling software, such as SimaPro, GaBi, or openLCA. If unable to conduct an LCA, we recommend selecting materials that are of closest proximity to the application site.

8. Use the preliminary LCA results (step 7, above) to guide your selection of candidate materials.

While the researchers conducted a formal LCA, they recognize that this is less common in standard practice. If able to conduct an LCA, it is recommended to use LCA modeling software, such as SimaPro, GaBi, or openLCA. If unable to conduct an LCA, we recommend selecting materials that are of closest proximity to the application site

9. 3.3 Decision #3: Civil Engineering Analysis Example

1. For each granular, organic, and/or topsoil material with the potential to be used in the engineered soil mixture, perform a gradation test to identify the material's grain size distribution and classify it according to ASTM D6913-04.

Following sieve analysis, the grain size distribution curves shown in Figures 2 and 3. Following the Unified Soil Classification System described in ASTM D6913-04, the dredge and degritter classify as SM and SP, respectively.

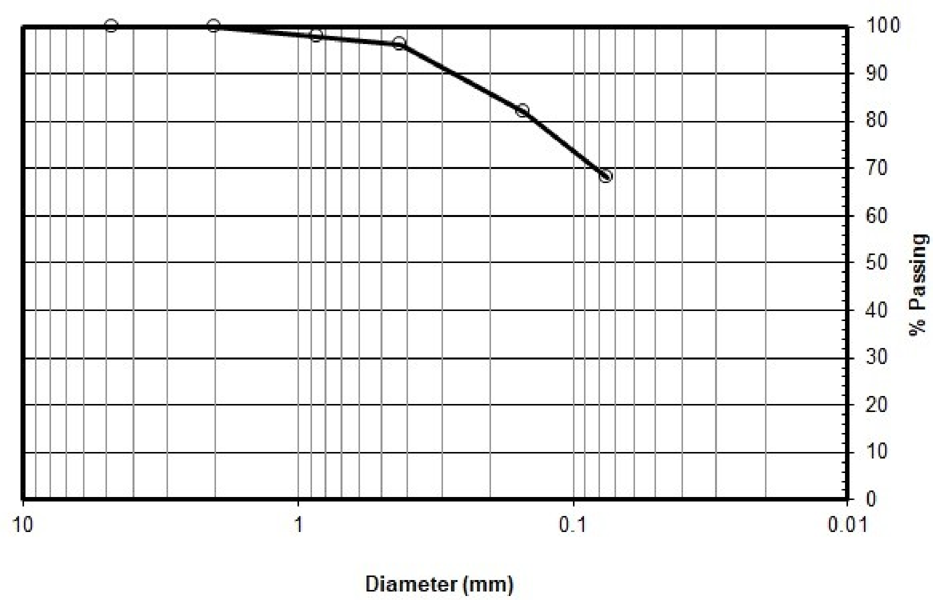

Figure 2. Grain size distribution curve for the dredge material considered in this example.

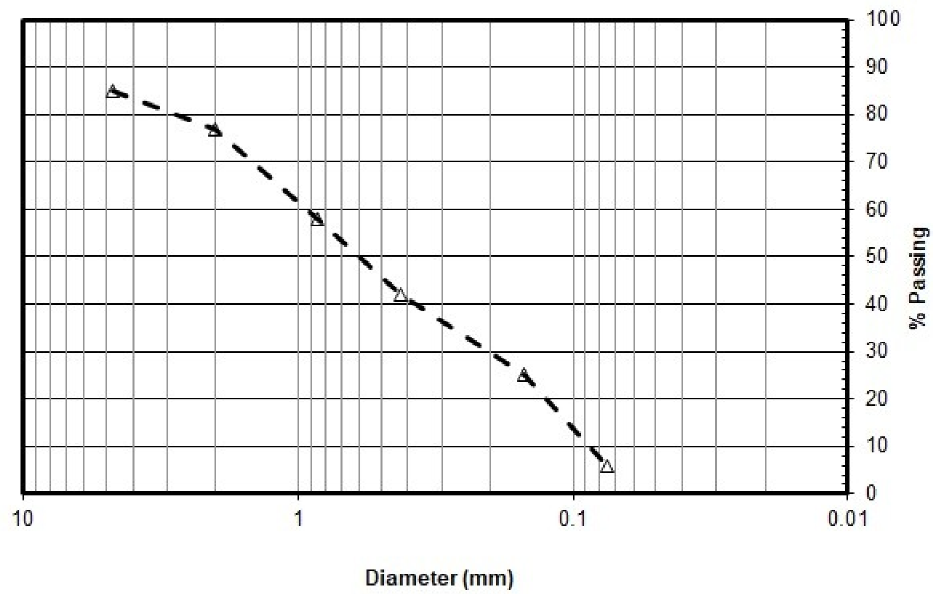

Figure 3. Grain size distribution curve for the degritter considered in this example.

2. Using the grain size data, predict the grain size of an engineered soil mixture. The weight retained on a given sieve should be multiplied by the material's percentage in the mix and added to the other material's weight retained on the same sieve after multiplying it by its percentage in the engineered soil mixture. The resulting engineered soil mixture data can be plotted to determine the factors required in the analysis described in Step 3.

Table 2 shows an example of the process used to determine grain size distribution in the engineering soil mixture using the grain size curves shown in Figures 2 and 3. The resulting predicted grain size curve for the engineered soil mixture is shown in Figure 4.

Table 2. Example determination of engineered soil mixture grain size.

Sieve Number	Grain Size (mm)	Material A Mass Retained (g)	Material A % in Engineered Soil Mixture	Material B Mass Retained (g)	Material B % in Engineered Soil Mixture	Engineered Soil Mixture Mass Retained (g)
#10	2.00	73.0	20	24.0	80	73 g x 0.2 + 24 g x 0.8 = 33.8 g

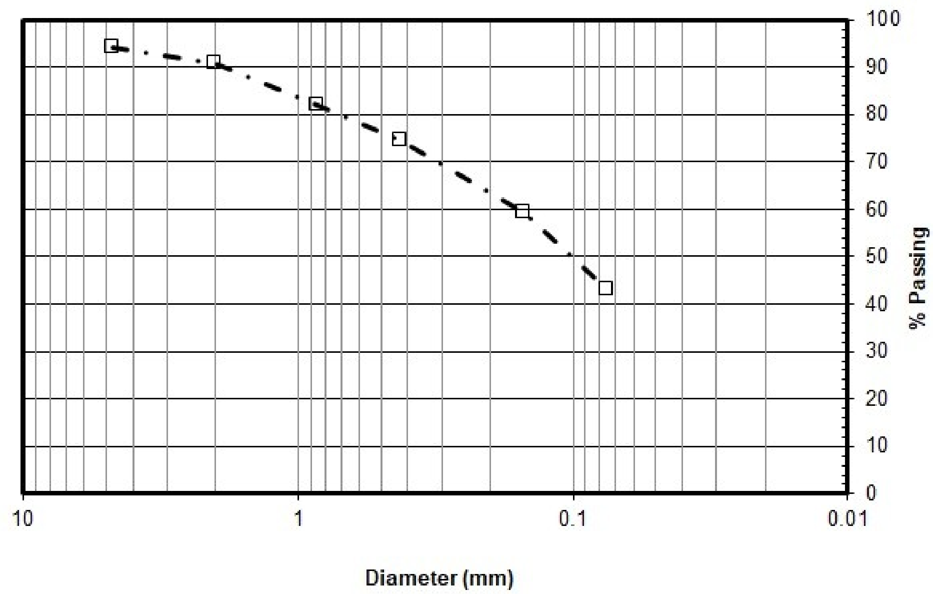

Figure 4. Grain size distribution curve for the engineered soil mixture of 60% dredge material and 40% degritter considered in this example.

3. Predict the engineered soil mixture's hydraulic conductivity using the relationships proposed by Kozeny-Carmen, shown in Equation 1; Moulton, shown in Equation 2; and Beyer, shown in Equation 3. Johnson et al. (2019), Saftner et al. (2024), and Ishaku et al. (2010) showed that Kozeny-Carmen typically slightly overpredicts actual hydraulic conductivity while Moulton and Beyer generally underpredict actual hydraulic conductivity.

The following examples show how the authors used Equations 1 through 3 to predict permeability using the grain size distribution of the engineered soil mixture, presented in Figure 4.

Kozeny-Carmen equation

While there are numerous approaches the using the Kozeny-Carmen equation, the approach presented here follows that described by Coduto et al. (2011). Carrier (2003) demonstrated that T^2 is approximately 5 for most soils. Assuming perfectly spherical grains, the specific surface area would equal 6 divided by the sphere's diameter. As soil grains are not perfectly spherical, a shape factor, S_F, which varies between 6 for well-rounded soils and 8.4 for very angular soils, is used. Similarly, the diameter is not constant in soil, requiring a weighted average of the sieve opening in the larger sieve, D_{li}, and the sieve opening in the smaller sieve, D_{si}. Simplifying Equation 1, accounting for the unit weight and viscosity of water, therefore results in Equation 4.

$$k=1.99\times10^{4}\left(\frac{100\%}{\sum\left[f_i/\left(D_{li}^{0.404}\times D_{si}^{0.595}\right)\right]}\right)^{2}\left(\frac{1}{S_F}\right)^{2}\left(\frac{e^{3}}{1+e}\right) \qquad \text{Equation 4}$$

Where k is expressed in centimeters per second, f_i is the fraction of soil between the two sieve sizes, D_{li} is the sieve opening in the larger sieve, D_{si} is the sieve opening in the smaller sieve, S_F is the soil's shape factor, and e is the void ratio.

The researchers' laboratory characterization of these materials is more in depth than characterization expected in practice. So while the void ratio could be determined using weight-volume relationships to be 0.78, use of typical values based on soil type, referenced from, among other sources, textbooks used in undergraduate geotechnical engineering courses, is recommended in practice. This subangular soil had a shape factor of 6.6. The terms fi, Dli, and Dsi were determined from the grain size curve shown in Figure 4. Equation 5 shows determination of the predicted hydraulic conductivity in units of cm/sec.

$$k=1.99\times10^4\left(\frac{100\%}{\sum 1084\%}\right)^2\left(\frac{1}{6.6}\right)^2\left(\frac{0.78^3}{1+0.78}\right) \quad \text{Equation 5}$$

The predicted hydraulic conductivity using the Kozeny-Carmen equation was $1.0*10^0$ cm/sec.

<u>Moulton equation</u>

Using Figure 4, D_{10} is 0.02 mm and P_{200} is 43.2%. Porosity, n, is defined as the void ratio divided by one plus the void ratio. Using the void ratio of 0.78 determined above, the porosity is 0.44. Again, the void ratio was determined using characterization data beyond what would typically be available in practice and use of typical values is recommended. Equation 6 shows determination of the predicted hydraulic conductivity in units of ft/day.

$$k=\frac{6.214*10^5(0.02)^{1.478}(0.44)^{6.654}}{(43.2)^{0.597}} \quad \text{Equation 6}$$

The predicted hydraulic conductivity using the Moulton equation was $3.0*10^{-4}$ cm/sec

<u>Beyer equation</u>

Using Figure 4, d_{10} is 0.02 mm and d_{60} is 0.15 mm. Therefore, U, the coefficient of uniformity is 7.5. Gravitational acceleration is 9.81 m/sec^2 and the viscosity of water at 13°C is $1.2*10^{-6}$ m^2/sec. Equation 7 shows determination of the predicted hydraulic conductivity in units of m/sec.

$$k=\frac{9.81}{1.2\text{-}10^{-6}}*6.0*10^{-4}*\log\left(\frac{500}{7.5}\right)*(0.02)^2 \quad \text{Equation 7}$$

The predicted hydraulic conductivity using the Moulton equation was $3.6*10^{-4}$ cm/sec

4. Repeat steps 2 and 3, varying the percent of each granular, organic, and/or topsoil material in the engineered soil mixture, to determine potential engineered soil mixtures with Kozeny-Carmen predicted hydraulic conductivity over and Moulton & Beyer predicted hydraulic conductivity near the MnDOT minimum hydraulic conductivity of 10^{-3} cm/sec. Any engineered soil mixtures considered using the criteria described on page 3 of this guide should meet minimum hydraulic conductivity.

The Kozeny-Carmen predicted hydraulic conductivity exceeds MnDOT minimum required conductivity and both Moulton and Beyer predicted hydraulic conductivities are near MnDOT minimum required conductivity. Laboratory testing beyond that typical used in practice confirmed that the proposed mixture meets minimum MnDOT standards. For a more conservative design, one could increase the percentage of the material with the larger grain size until all prediction methods exceed MnDOT minimum standards. For the purposes of this example, the proposed mixture of 60% dredge material and 40% degritter meets the minimum hydraulic conductivity goals.

3.4 Decision #4: Environmental Engineering Analysis Example

1. Each granular, organic, and/or topsoil material with the potential to be used in the engineered soil mixture must not be listed on the EPA hazardous waste list.

Both dredge sediment and degritter originate from natural sources without any industrial processing. Neither of them is listed on the EPA hazardous waste list.

2. Materials not listed as hazardous waste need further testing for ignitability, corrosivity, reactivity, and toxicity using the EPA SW-846 test. The same test is also used to examine the concentrations of eight RCRA (Resource Conservation and Recovery Act) metals: arsenic, barium, cadmium, chromium, lead, mercury, selenium and silver. Any materials characterized as hazardous waste based on the test results are excluded from consideration.

Since dredge sediment is collected from harbor dredging and degritter is sourced from log washing, neither material is ignitable or reactive.

A corrosivity test is required only when the aqueous waste has a pH of less than or equal to 2, a pH greater than or equal to 12.5, or if the liquid has the ability to corrode steel. Both dredge sediment and degritter were tested to be neutral, with pH values of 7.2 and 7.6, respectively. Therefore, no corrosivity test is necessary.

Toxicity tests were conducted on dredge sediment for RCRA metals (As, Ba, Cd, Cr, Pb, Hg, Se, and Ag), with the following results: 2.7, 64.4, 0.23, 18.7, 11.9, 0.085, <1, and <0.56 mg/L, respectively. Most of these levels were below EPA limits. Toxicity testing was not performed for degritter because neither the logs nor the washing process is expected to introduce significant metal content. RCRA metal test is recommended to be performed by a commercial laboratory.

3. For the non-hazardous materials, analyze for Polychlorinated Biphenyls (PCBs), Polycyclic Aromatic Hydrocarbons (PAHs), and Volatile Organic compounds (VOCs) using the EPA SW-846 test by a certified lab, comparing measured values with MPCA soil reference values (SRVs) to ensure contents fall below specified thresholds.

Tests for PCBs, PAHs, and VOCs are recommended to be conducted by a commercial laboratory. For the dredge sediment, no PCBs or VOCs were detected, and PAH contents were below 130 µg/kg, which is significantly lower than the soil reference values (all detected compositions have SRVs above 1,000 µg/kg). This test was not performed for degritter, as this material consists of natural logs and debritter.

4. Materials selected from Step 3 also need to be characterized for pH, organic matter content, nutrients (nitrogen, phosphorus, potassium), cations (calcium, magnesium), and soluble salts by a

qualified lab. This step aims to gather data on nutrient levels to support plant growth and determine any necessary supplemental mixing.

Nutrient contents are typically analyzed by a soil lab to determine if the material is suitable for vegetation growth. The parameters that must be included in this analysis are pH, percent of organic matter, phosphorus, nitrogen, potassium content, and soluble salts. These data will be used to determine if the material can solely support vegetation growth and which nutrients need to be supplemented. Table 3 shows both materials are neutral with intermediate content of phosphorus, and low soluble salts. Potassium content is intermediate for dredge sediment and very high for degritter.

Table 3. Nutrient contents of dredge sediment and degritter

Parameters	Dredge sediment	Degritter
pH	7.2	7.6
%OM	3	18.9
Olsen P, ppm	NA	10
Bray P, ppm	13	15
K, ppm	75	299
NO3_N, ppm	33.1	2.1
Soluble Salts, mmhos/cm	0.7	0.5

5. The granular, organic, and/or topsoil material selected from Step 3 is mixed with deionized water to assess potential leaching concentrations, comparing them against standards to prevent chemical leachate pollution of receiving water bodies. The recommended mixing procedure involves combining the solid with deionized water at a raito of 1:10 and mixing for 24 hours. The final chemical concentrations in the liquid determine the amount of chemical released. The mixing ratio and duration can be adjusted based on specfific applications.

This procedure is designed to determine if any pollutants with significant concentrations will be released from the material. It simulates application conditions without using a standard method. For example, if the material is applied in a detention pond where it is continuously soaked in water, it is recommended to place the material in DI water for an extended period until equilibrium is reached. When the material is used as filtration media, a 24-hour mixing period is recommended. The typical mixing ratio of solid to liquid is 1:10, but this can be adjusted based on potential pollutant concentration for easier measurement by instruments. For dredge sediment, no copper or lead was detected in the water, and the release concentrations of zinc and phosphate were 2.2 and 2.4 µg/kg, respectively. For degritter, the detected amounts of copper, zinc, and phosphate were 1.51, 0.45, and 0.03 µg/g, respectively. In general, the release concentration for dredge sediment is quite low. The relatively high contents of metals and phosphate in degritter suggest that it should be mixed with other materials in relatively small proportions.

6. Materials selected from Step 3 are recommended for mixing with synthesized stormwater following the procedure in Step 5 to evaluate their capacity to remove runoff contaminants, informing decisions on additional materials needed for optimizing stormwater runoff treatment. It is recommended that the work in both Steps 5 & 6 be conducted by a research lab with expertise in batch testing with soil materials.

The procedure from Step 5 should be applied here, with the exception that synthesized pond water or stormwater is used to simulate the application scenario. In a 24-hour mixing test, both sediment and degritter demonstrated the ability to remove more than 60% of copper, lead, zinc, and phosphate from the water, with particularly effective removal of copper exceeding 90%. This information can be used to estimate the potential treatment capacity of the materials.

7. Review study materials against new standards or methods to ensure ongoing compliance and environmental safety.

Emerging contaminants, such as PFAS, are currently being studied. Regulation of concentration limits and standard analysis methods are still being developed. In addition to the analyses conducted, it is important to stay updated on new regulations and methods to ensure any necessary additional analyses are performed.

The proposed mixture of 60% dredge material and 40% degritter meets the minimum environmental engineering goals.

3.5 Decision #5: Plant Growth Analysis Example

To effectively select the materials to be applied in the engineered soil mixtures for roadside applications, ensuring that the selected materials can facilitate plant growth is essential. This involves a process conducted through greenhouse testing for individual media, outlined below:

1. Greenhouse Testing for Invasive Species. The first step involves conducting greenhouse tests to examine whether the media contains invasive plant species. This is achieved by regularly watering individual organic and/or topsoil materials placed in pots within a greenhouse for at least two months. The objective is to observe any spontaneous plant growth without the introduction of seeds and to identify if these plants belong to any invasive species lists. If the invasive species are detected, the material must undergo pre-treatment to eliminate them before further application.

For this test, simply place the material in 3 or more pots to ensure reliable results. If a greenhouse is not available, place the pots in a warm place with sufficient sunlight and no other plants. Regularly water the pots to maintain adequate moisture levels in the material. Monitor for any signs of plant growth and identify if any belong to invasive species. The U.S. Army Corps conducted this test on dredge sediment and identified several invasive species. The exact source of these invasive species is unclear, as the sediment itself was stored in the harbor for several years. Users should be informed of this information to determine if any pre-treatment is necessary before using this material.

2. Collaborate with MnDOT for Seed Selection. Collaborate closely with MnDOT to determine the appropriate grass or plant seeds for roadside application. These seeds will be carefully selected to conduct plant growth tests in the greenhouse.

This step involves preparing for the plant growth test. The selected seeds should be appropriate for the application scenario. MnDOT provides a guide for the seed mix. If specific seed information is not available, it is recommended to use one broadleaf species and one narrowleaf species for testing. In the materials studied, oat and radish were used for the test. However, since radish is typically not used for roadside applications, it is not recommended for the plant growth test.

3. Plant Growth Assessment. Materials not containing any invasive species are tested with the seeds identified in Step 2 to assess germination rates and subsequent plant growth. Measurements, including germination rates, plant height, and biomass, are taken to evaluate the ability of each material to independently support plant growth. Any materials found to be insufficient in supporting plant growth on their own will require supplementation with additional materials.

For dredge sediment and degritter, growth tests were conducted in a greenhouse for 21 days. Six replicated pots were used for each material with one type of seed. The germination rate was estimated on the 7th day. After 21 days, biomass and above-ground height were measured. Both materials supported the growth of oats and radishes very well, indicating that each material has the potential to be applied in the field.

3.6 Decision #6: Engineered Soil Mixture Performance Analysis Example

Following the characterization data of individual granular, organic, and/or topsoil materials identified by Decisions #2, #3, and #4, the materials are carefully chosen to formulate the engineered soil mixture. However, additional plant growth testing is required to assess the mixture’s efficacy in supporting plant growth and to ascertain the necessity of additional fertilization for optimal application.

1. Conduct plant growth tests for soil mixtures using the grass or plant species selected by MnDOT. A reference media should also be included for performance evaluation. Mixtures unable to sustain plant growth should be excluded from consideration.

This step is to further test if the selected soil mixture can support plant growth. The same procedure used in Decision #5 Step 3 is applied here, but using the soil mixture as the testing media. At this step, a reference material, like compost is recommended to be conducted to examine if the growth rate meets the criteria.

2. Mixtures capable of supporting plant growth but exhibiting lower height or biomass than the reference media require supplementation with fertilizer. The frequency of fertilization depends on the growth condition. The choice of fertilizer can be determined based on the nutrient content identified in Step 4 of Decision #3.

The comparison with reference media will determine if additional fertilizer is needed. For the type of fertilizer, check the nutrient contents measured in Step 4 of Decision #3. For dredge sediment and degritter, it appears that nitrogen supplementation may be necessary. Degritter has little nitrogen, and the nitrogen content in dredge sediment is slightly lower than 40 ppm, a typical value required for a garden. The proposed mixture of 60% dredge material and 40% degritter meets the minimum plant growth goals.

Overall, the results of this analysis show that the combination of 60% dredge material and 40% degritter would work well for an engineered soil mixture for use in a detention application.

APPENDIX B: NUTRIENT CONTENTS AND BIOMASS OF WASTE MATERIALS

Table 1 Summary table of the environmental properties and specifications for the studied nine materials.

Property	**Ash sawdust**	**Bottom ash**	**Degritter**	**Dredge sediment**	**Lime mud**	**Peat/Biochar mix**	**Pine sawdust**	**Recycled concrete aggregate**	**VersaLime**
pH	Acidic	Basic	Neutral	Neutral	Basic	Neutral	Acidic	Basic	Basic
Copper leaching	Minimal	Slight	Slight	Minimal	Minimal	Minimal	Minimal	Minimal	Slight
Copper retention	Significant	Significant	Significant	Minimal	Significant	Significant	Significant	Significant	Slight
Lead leaching	No	Minimal	No	Minimal	Minimal	No	No	No	No
Lead retention	Significant	Significant	Significant	Slight	Slight	Significant	Significant	Significant	Significant
Zinc leaching	Minimal	Minimal	Minimal	Minimal	Slight	Minimal	Slight	Minimal	Minimal
Zinc retention	Significant	Significant	Significant	minimal	Significant	Significant	Significant	Significant	Significant
Phosphorus leaching	Significant	No	Slight	No	No	Minimal	Slight	No	Slight

Phosphorus retention	No	Significant	Slight	Minimal	Significant	Slight	Minimal	Slight	Significant
Nitrate leaching	Minimal	Slight	No	Minimal	Slight	Significant	No	Slight	Slight
Nitrate retention	Slight	Slight	Slight	Minimal	Minimal	Minimal	Minimal	Slight	Significant
PFAS leaching	Potential	Potential	Potential	No	No	Potential	Potential	Potential	No
Plant growth	Good	No	Good	Good	No	Slight	Good	Good	No

Table 2 The nutrient contents of seven waste materials.

Waste Name	Botto m ash	Degritter	Lime mud	Dredge sediment	Recycled concrete aggregate	VersaLime	Peat/biochar mix
Organic Matter, %	5.7	18.9	3.1	0.1	1.8	10	73.7
Soluble Salts, mmhos/cm	9.5	0.5	25	0.1	3.2	2.9	0.2
pH	12	7.6	12	8.9	10.2	10	7.3
Nitrate NO3-N, ppm	3.1	2.1	3	0.6	3.8	8.1	1.9
Olsen Phosphorus , ppm P	50+	10	45	4	4	50+	
Bray 1 Phosphorus , ppm P	2	15	2	13	2	3	4
Potassium, ppm K	300+	299	300+	11	226	237	265
Sulfur SO4S, ppm	32	33	40+	2	40+	40+	23

Zinc, ppm	0.1	14.4	1.4	0.5	3.7	2.3	1.3
Iron, ppm	46.3	35.2	25	9.7	15.4	39	127.8
Manganese, ppm	0.6	32.4	0.3	3.1	3.8	9.6	17.4
Copper, ppm	0.9	1.1	2.6	0.1	2.6	2	0.1
Calcium, ppm	10000	3075	10000	230	5955	6850	2460
Magnesium, ppm	99	262	179	29	46	3429	249

Table 3 The mean (standard deviation) of the number of live plants observed on the 7th day and the 21st day, and the total biomass of each pot (six seeds each pot) after the seeds were applied for 21 days. The mean values were compared by Tukey-Kramer HSD among the media (each column within one plant). The different letters represent the significant differences ($p<0.05$).

Waste Name	**Number of plants after seed applied for 7 days**	**Number of plants after seed applied for 21 days**	**Total biomass of each pot, g**	**Total height of each pot, cm**
	Oat			
Ash Sawdust	5.67 (0.52)A	6.00 (0)A	0.20 (0.02)CDE	80.45 (10.84)BC
Pine Sawdust	5.17 (1.47)A	6.00 (0.89)A	0.23 (0.08)BCDE	65.28 (21.64)C
Degritter	4.50 (1.38)A	5.67 (0.82)A	0.28 (0.04)ABC	68.45 (8.21)C
Peat/biochar mix	1.33 (1.51)B	5.50 (0.84)A	0.18 (0.04)DE	85.33 (30)BC
Bottom Ash	0.17 (0.41)B	0.33 (0.52)C	0.02 (0.03)F	2.02 (3.18)D
Dredge Sediment	5.83 (0.75)A	6.00 (0)A	0.33 (0.04)A	78.33 (7.72)BC
RCA	4.33 (1.75)A	6.17 (0.41)A	0.32 (0.04)AB	75.88 (13.61)C
Lime Mud	0B	0C	0F	0D
VersaLime	0B	2.50 (1.38)B	0.14 (0.07)E	10.70 (8.22)D

Dredge Sediment (80%) + Degritter (20%)	5.83 (0.41)A	5.83 (0.41)A	0.28 (0.06)ABCD	108.25 (14.07)B
RCA (80%) +Ash saw dust (20%)	5.83 (0.41)A	5.83 (0.41)A	0.27 (0.05)ABCD	93.09 (10.23)BC
RCA (80%+peat/biochar mix (20%)	5.50 (0.84)A	5.67 (0.82)A	0.27 (0.08)ABCD	144.68 (27.78)A
	Radish			
Ash Sawdust	2.00 (2.10)BC	4.83 (0.98)A	0.04 (0.01)CD	9.10 (3.19)D
Pine Sawdust	4.00 (1.26)AB	5.67 (1.03)A	0.11 (0.01)B	8.23 (2.55)D
Degritter	4.33 (1.21)AB	4.83 (0.75)A	0.11 (0.03)B	9.82 (2.40)D
Peat/biochar mix	0.33 (0.52)C	2.00 (0.89)B	0.04 (0.03)CD	7.32 (4.15)DE
Bottom Ash	0C	0C	0D	0E
Dredge Sediment	4.50 (1.52)AB	5.50 (0.55)A	0.19 (0.04)A	13.30 (2.93)CD
RCA	4.17 (2.32)AB	5.33 (0.82)A	0.12 (0.02)B	10.95 (2.51)D
Lime Mud	0C	0C	0D	0E

VersaLime	0C	0C	0D	0E
Dredge Sediment (80% + Degritter (20%	5.83 (0.41)A	5.83 (0.41)A	0.11 (0.02)B	29.70 (3.35)A
RCA (80%+Ash saw dust (20%	4.83 (0.98)A	5.50 (0.84)A	0.08 (0.03)BC	18.93BC
RCA (80%+peat/biochar mix (20%	4.67 (1.75)A	5.00 (1.26)A	0.12 (0.05)B	26.25 (8.65)AB