



(REVIEW ARTICLE)



Soil media innovations in bioswales: A review of engineered amendments and their influence on hydraulic and pollutant removal performance

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Abstract

Bioswales represent an essential green infrastructure component for sustainable stormwater management in urban environments. This review examines recent innovations in soil media design and engineered amendments for bioswales, focusing on their influence on both hydraulic performance and pollutant removal efficiency. The study systematically evaluates various soil amendment strategies, including biochar incorporation, iron-enhanced media, and specialized composite mixes designed to target specific pollutants. Research findings indicate that properly engineered soil media can significantly enhance bioswale performance, with documented improvements in infiltration rates, water retention capacity, and removal efficiencies for common stormwater pollutants such as suspended solids, nutrients, heavy metals, and organic contaminants. The review highlights the importance of amendment selection based on site-specific conditions, target pollutants, and local climate factors. Finally, this paper identifies critical knowledge gaps and promising research directions for advancing the next generation of bioswale soil media technologies.

Keywords: Bioswales; soil amendments; Stormwater management; Pollutant removal; Hydraulic performance; biochar; Iron-enhanced media; Engineered soils

1. Introduction

The rapid expansion of urban environments worldwide has dramatically altered natural hydrological cycles, resulting in significant environmental challenges. Increased impervious surface coverage from roads, buildings, and parking lots has led to higher volumes and peak rates of stormwater runoff, reduced groundwater recharge, and degraded water quality in receiving water bodies (Walsh et al., 2005; National Research Council, 2009). Concurrently, climate change is intensifying these challenges through more frequent and intense precipitation events in many regions (IPCC, 2014). In urbanized areas, conventional stormwater management approaches that focus primarily on flood control through rapid conveyance and detention have proven inadequate for addressing these complex challenges.

The negative impacts of urban stormwater runoff extend beyond hydrology to encompass significant water quality concerns. Urban runoff typically contains elevated levels of suspended solids, nutrients (nitrogen and phosphorus), heavy metals, petroleum hydrocarbons, pathogens, and other contaminants that can severely impair aquatic ecosystems and limit beneficial uses of receiving waters (Göbel et al., 2007; Hatt et al., 2009). Traditionally, these pollutants have been treated through end-of-pipe solutions such as detention basins and constructed wetlands, which often have limited effectiveness for a comprehensive range of pollutants and insufficient capacity to manage increasing stormwater volumes.

In response to these challenges, a paradigm shift in stormwater management has emerged, emphasizing decentralized, source-control approaches that mimic natural hydrological processes. This approach, commonly known as Low Impact

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Development (LID) in North America, Sustainable Urban Drainage Systems (SUDS) in the United Kingdom, or Water Sensitive Urban Design (WSUD) in Australia, represents a more integrated and ecologically-based philosophy (Dietz, 2007; Roy et al., 2008). Green infrastructure has become the physical manifestation of this approach, encompassing a suite of techniques and practices that utilize vegetation, soils, and natural processes to manage stormwater at its source while providing multiple environmental, social, and economic benefits (Fletcher et al., 2015).

1.1. Bioswales as Green Infrastructure Elements

Among various green infrastructure elements, bioswales have emerged as particularly effective stormwater management tools, especially along linear transportation corridors and in sites with space constraints. Bioswales, also known as vegetated swales or linear bioretention systems, are shallow landscape depressions designed to capture, convey, and treat stormwater runoff while directing it to infiltration areas or engineered containment systems (Dietz & Clausen, 2008; Hunt et al., 2012). These systems leverage the natural processes of filtration, infiltration, adsorption, and biological uptake to reduce runoff volumes and improve water quality before discharge to receiving waters.

The evolution of bioswale design has progressed from simple grassed channels focused on conveyance to sophisticated multi-functional systems that balance hydrologic, water quality, ecological, and aesthetic objectives. Early bioswale designs in the 1980s primarily emphasized infiltration and peak flow reduction, with limited attention to water quality enhancement (Schueler, 1987). By the early 2000s, research began to document the water quality benefits of vegetated swales, though performance was often inconsistent and dependent on design parameters and maintenance practices (Barrett et al., 2004; Deletic & Fletcher, 2006).

The period from 2014 to 2017 witnessed significant advancements in bioswale design, with a particular focus on enhancing pollutant removal capabilities through specialized soil media formulations. This shift reflected growing recognition that while standard soil mixes could achieve basic hydrologic functions, they often fell short in removing dissolved pollutants such as nutrients, metals, and organic contaminants consistently. Research during this period increasingly explored the potential for engineered amendments to target specific pollutants while maintaining essential hydraulic functions (Li & Davis, 2014; Trowsdale & Simcock, 2011).

1.2. Importance of Soil Media in Bioswale Performance

The performance of bioswales is heavily dependent on their soil media composition, which functions as the primary interface for both hydraulic management and pollutant removal processes. Engineered media typically consists of mixtures of sand, fines (silt, clay), and organic matter designed to achieve rapid infiltration rates, attenuate pollutants, and support healthy plant growth (Hunt et al., 2012). The media must balance competing objectives, including sufficient permeability for stormwater infiltration, adequate water holding capacity for vegetation, and appropriate chemical and physical properties for pollutant removal.

Recent advances in soil media design have focused on enhancing these functions through innovative amendments and media formulations. These specialized amendments aim to overcome limitations observed in conventional bioswale media, particularly for the removal of dissolved nutrients, metals, and organic contaminants (Davis et al., 2009; LeFevre et al., 2015). Various researchers have investigated amendments such as biochar, iron-based compounds, water treatment residuals, and other materials with specific pollutant-targeting capabilities.

The emergence of these innovative soil media formulations represents an important frontier in bioswale technology, with the potential to significantly enhance their environmental performance and applicability across diverse settings. Understanding the capabilities, limitations, and optimal design considerations for these engineered amendments is essential for advancing bioswale design and implementation.

1.3. Scope and Objectives of the Review

This review examines significant developments in bioswale soil media research from 2014 to 2017, focusing on engineered amendments and their influence on both hydraulic performance and pollutant removal efficiency. The specific objectives of this review are to:

- Characterize the fundamental components and design considerations for bioswale soil media
- Evaluate emerging amendments and their influence on media performance
- Assess hydraulic performance impacts associated with various media formulations
- Analyze pollutant removal mechanisms and efficiencies for key urban stormwater contaminants
- Review case studies demonstrating field-scale implementation of innovative bioswale media

- Identify best practices for media selection, installation, and maintenance
- Highlight knowledge gaps and promising research directions

The paper is structured to provide a comprehensive overview of media composition strategies, evaluate performance data from field and laboratory studies, and identify emerging trends and research gaps in bioswale media development. By synthesizing research findings from this critical period, this review aims to inform the next generation of bioswale designs and foster continued advancement in green infrastructure practices for urban stormwater management.

2. Bioswale Fundamentals and Design Considerations

2.1. Definition and Function

Bioswales are linear, vegetated drainage channels designed to manage stormwater through a combination of conveyance, infiltration, and filtration functions. They consist of a swaled drainage course with gently sloped sides, planted with vegetation that slows water flow and facilitates pollutant removal. Unlike conventional drainage ditches, bioswales are engineered systems that incorporate specialized soil media to enhance performance.

The primary functions of bioswales encompass both hydrological management and water quality improvement:

2.1.1. Hydrological Functions

- **Flow attenuation:** Reducing peak discharge rates through temporary detention
- **Volume reduction:** Decreasing runoff volumes through enhanced infiltration and evapotranspiration
- **Conveyance:** Safely transporting stormwater to designated discharge points
- **Groundwater recharge:** Promoting infiltration to replenish groundwater resources where appropriate

2.1.2. Water Quality Functions

- **Sedimentation:** Capturing suspended solids through settling processes
- **Filtration:** Physically removing particulate pollutants as water passes through vegetation and media
- **Adsorption:** Binding dissolved pollutants to soil particles and specialized amendments
- **Biogeochemical processing:** Transforming pollutants through biological and chemical reactions
- **Plant uptake:** Removing nutrients and certain contaminants through vegetation

Bioswales differ from traditional drainage ditches and grass swales in their intentional design to maximize these functions through carefully engineered dimensions, soil media, vegetation selection, and additional structural elements. The engineering of these systems has evolved substantially, with early designs focused primarily on conveyance and later iterations incorporating increasingly sophisticated approaches to water quality improvement (Yu et al., 2001; Davis et al., 2012).

Bioswales can be classified into several subtypes based on their specific design objectives and site contexts:

- **Basic vegetated swales:** Simple, grass-lined channels with moderate pollutant removal
- **Enhanced dry swales:** Incorporate engineered soil media for improved filtration and infiltration
- **Wet swales:** Include saturated zones or small pools for enhanced nutrient processing
- **Bioinfiltration swales:** Designed to maximize infiltration in areas with permeable native soils
- **Linear bioretention:** Combine elements of bioretention systems with linear conveyance functions
- **Check dam bioswales:** Include small dams or weirs to increase retention time and pollutant removal

The selection of appropriate bioswale type depends on site-specific factors including contributing drainage area, slope, native soil properties, pollutants of concern, and available space (Hunt et al., 2012; Eckart et al., 2017).

2.2. Typical Bioswale Components

A standard bioswale system typically includes the following structural components:

- **Inlet structure:** Directs stormwater runoff into the bioswale through curb cuts, pipes, or sheet flow. Proper inlet design is critical for preventing erosion and ensuring even distribution of flow. Common designs include curb cuts with energy dissipators, level spreaders, and rock aprons (Winston et al., 2010).

- **Pretreatment area:** Captures gross solids and sediment before water enters the main treatment section. Pretreatment extends the functional life of the system by reducing maintenance frequency and preventing clogging. Options include forebays, vegetated filter strips, and rock diaphragms (Hathaway & Hunt, 2010).
- **Vegetation layer:** Slows water flow, facilitates evapotranspiration, and contributes to pollutant removal. Plants provide physical filtration, stabilize soil media, enhance infiltration through root channels, and support microbial communities that process pollutants. Species selection should consider tolerance to periodic inundation, drought resistance, pollutant uptake capabilities, and aesthetic value (Read et al., 2008; Barrett et al., 2013).
- **Engineered soil media:** Provides filtration, pollutant removal, and supports vegetation. This critical component will be explored in detail throughout this review, as its composition strongly influences system performance. The media must balance multiple functions including structural support, infiltration capacity, pollutant adsorption, and plant growth support (Li & Davis, 2014).
- **Optional underdrain system:** Collects treated water when infiltration into native soil is limited by low permeability, high groundwater tables, or contamination concerns. Underdrains typically consist of perforated pipes embedded in a gravel drainage layer, sometimes with controls to create internal water storage zones for enhanced treatment (Brown & Hunt, 2011).
- **Overflow structure:** Manages excess flows during intense storm events, typically designed to safely convey the peak discharge from large storms (e.g., 10-year or 100-year events) without erosion or flooding. Common designs include elevated catch basins, weirs, or level spreaders (Davis et al., 2012).

2.3. Key Design Parameters

Several design parameters influence the hydraulic and water quality performance of bioswales. The optimization of these parameters requires balancing multiple objectives and accounting for site-specific constraints:

2.3.1. Geometric Parameters

- **Length:** Bioswale length significantly impacts residence time and treatment opportunity. Research by Lucke et al. (2014) demonstrated that the first 10m of swale length typically removed 50-80% of TSS, with diminishing returns beyond this length. However, longer bioswales may be necessary for volume reduction objectives or in areas with intense rainfall patterns. Recommended length-to-width ratios typically range from 3:1 to 10:1 (Jurries, 2003).
- **Width:** Cross-sectional width affects flow capacity, treatment surface area, and construction feasibility. Typical bottom widths range from 0.6 to 2.4 meters, with side slopes ranging from 3:1 to 5:1 (horizontal) for stability and maintenance access (Hathaway & Hunt, 2010). Wider swales generally provide better treatment but require more space.
- **Depth:** The bioswale profile depth includes both the ponding depth (typically 15-30 cm) and the media depth (typically 45-90 cm). Deeper media provides greater storage volume and treatment capacity but increases construction costs. Hunt et al. (2012) found that media depths greater than 60 cm generally produced optimal pollutant removal for most contaminants.
- **Longitudinal slope:** The slope along the bioswale's length affects flow velocity, erosion potential, and residence time. Optimal slopes typically range from 0.5% to 4%. Slopes below 0.5% may lead to standing water, while slopes above 4% may cause excessive flow velocities and erosion. On steeper sites, check dams or terracing can create a more suitable effective slope (Winston et al., 2010; Davis et al., 2012).

2.3.2. Media Parameters

- **Soil media composition:** The physical and chemical properties of the engineered soil media control infiltration rates, water storage capacity, and pollutant removal mechanisms. Key parameters include:
 - Grain size distribution (typically dominated by sand with limited fines)
 - Organic matter content (typically 3-10% by volume)
 - Cation exchange capacity (for metal and nutrient binding)
 - pH (typically maintained between 6.0 and 8.0)
 - Specialized amendments (biochar, iron filings, etc.)

Media composition must be carefully engineered to balance infiltration and treatment objectives, as will be discussed extensively in subsequent sections of this review.

- **Hydraulic conductivity:** The saturated hydraulic conductivity of bioswale media typically ranges from 2.5 to 30 cm/hr (5 to 60 in/day). Lower rates maximize contact time but risk surface ponding and bypass flow, while

higher rates improve volume reduction but may reduce treatment effectiveness for certain pollutants (Brown & Hunt, 2011).

2.3.3. Vegetation and Drainage Parameters

- **Vegetation selection:** Plant species influence hydraulic roughness (Manning's n value), evapotranspiration rates, root zone development, and biological processes. Vegetation should be selected based on:
 - Tolerance to periodic inundation and drought
 - Root structure (fibrous root systems enhance infiltration)
 - Growth habit (dense, uniform coverage maximizes filtration)
 - Pollutant uptake capabilities (particularly for nutrients)
 - Climate appropriateness and maintenance requirements

Research by Read et al. (2008) and Barrett et al. (2013) highlighted the significant role of vegetation in enhancing pollutant removal performance beyond what could be achieved through media filtration alone.

- **Drainage area ratio:** The ratio of contributing drainage area to bioswale surface area influences hydraulic loading and system performance. Recommended ratios typically range from 5:1 to 20:1 depending on climate, soil conditions, and design objectives (Hunt et al., 2015). Smaller ratios generally produce better performance but require more space and cost.
- **Internal water storage:** Some advanced bioswale designs incorporate saturated zones through upturned elbows on underdrains or impermeable liners. These zones enhance nitrogen removal through denitrification and can improve removal of certain metals and organic compounds (Kim et al., 2003; Brown & Hunt, 2011).

The optimal configuration of these design parameters depends on specific project objectives, site constraints, local climate, and regulatory requirements. Increasingly, bioswale design has moved toward performance-based approaches rather than prescriptive specifications, with modeling and monitoring used to optimize designs for particular applications (Eckart et al., 2017).

2.4. Performance Objectives

Bioswales are typically designed to meet specific performance objectives that extend beyond simple stormwater conveyance to address multiple environmental, regulatory, and community benefits:

2.4.1. Hydraulic Management Objectives

The primary hydraulic objectives of bioswale systems include:

- **Peak flow reduction:** Bioswales attenuate runoff hydrographs by temporarily storing stormwater and releasing it at a controlled rate. Research by Davis et al. (2012) demonstrated peak flow reductions of 40-70% for properly designed systems. This function is particularly valuable for reducing downstream erosion and flooding risks.
- **Volume reduction:** Through infiltration and evapotranspiration, bioswales can significantly reduce the total volume of stormwater entering receiving waters. Field studies by Xiao & McPherson (2011) documented runoff volume reductions of up to 88.8% in a parking lot bioswale, while Lucke et al. (2014) reported volume reductions between 30-52% for roadside applications.
- **Flow velocity control:** The vegetation and gentle slopes of bioswales reduce flow velocities, preventing erosion and increasing residence time for treatment processes. Typical design standards aim to maintain non-erosive velocities below 0.3 m/s for frequent storm events (Jurries, 2003).
- **Conveyance capacity:** While emphasizing treatment functions, bioswales must still safely convey design flows without causing flooding or property damage. Most designs include capacity for at least the 10-year storm event, with safe overflow paths for larger events (Winston et al., 2010).

2.4.2. Water Quality Improvement Objectives

Water quality performance objectives typically focus on:

- **Suspended solids removal:** TSS reduction is often considered a primary indicator of bioswale performance, with typical design targets of 80-90% removal. Suspended solids removal correlates with reductions in particulate-bound pollutants and turbidity improvement (Hathaway & Hunt, 2010).

- **Nutrient management:** Bioswales are increasingly designed to target nutrients, particularly phosphorus and nitrogen, which contribute to eutrophication of receiving waters. Advanced systems with specialized media can achieve 30-70% total phosphorus removal and 25-60% total nitrogen removal (Hunt et al., 2012).
- **Heavy metal reduction:** Urban runoff often contains elevated concentrations of metals such as zinc, copper, and lead. Bioswales can remove 60-95% of these metals through filtration, adsorption, and precipitation processes (Davis et al., 2009; LeFevre et al., 2015).
- **Pathogen reduction:** While not always a primary design objective, bioswales can reduce pathogen concentrations through filtration, predation, and UV exposure. Reductions of 60-90% for indicator bacteria have been documented in well-designed systems (Hathaway et al., 2011).
- **Hydrocarbon and organic pollutant removal:** Bioswales can effectively remove petroleum hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), and other organic contaminants through adsorption to organic matter and biodegradation by soil microorganisms (LeFevre et al., 2012).

2.4.3. Additional Functional Objectives

Beyond hydraulic and water quality functions, contemporary bioswale design often incorporates:

- **Groundwater recharge:** In areas with suitable soils and groundwater conditions, bioswales can help replenish groundwater resources, offsetting the impacts of impervious surfaces on the hydrologic cycle. This function is particularly valuable in water-scarce regions or areas with declining aquifer levels (Dillon et al., 2009).
- **Urban heat island mitigation:** Through increased evapotranspiration and reduced impervious surface coverage, bioswales can help lower ambient temperatures in urban areas. Studies by Coutts et al. (2013) documented temperature reductions of 2-4°C in and around green infrastructure elements.
- **Carbon sequestration:** Bioswales with appropriate vegetation and soil media composition can sequester carbon in biomass and soil organic matter, contributing modestly to climate change mitigation efforts (Pataki et al., 2011).
- **Habitat provision:** Well-designed bioswales can create ecological corridors and habitat patches for birds, pollinators, and other urban wildlife, enhancing urban biodiversity (Kazemi et al., 2011).
- **Landscape enhancement:** Beyond their functional performance, bioswales can provide aesthetic benefits, increase property values, and create recreational opportunities in urban environments. These co-benefits often help justify implementation costs and increase community acceptance (Nassauer, 2004).

Performance objectives are increasingly codified in stormwater regulations and design standards, with many jurisdictions adopting performance-based approaches that specify quantitative targets for volume reduction, peak flow control, and pollutant removal. The achievement of these objectives depends heavily on proper design, construction, and maintenance practices, with soil media composition playing a particularly critical role in long-term performance (Hunt et al., 2015; Eckart et al., 2017).

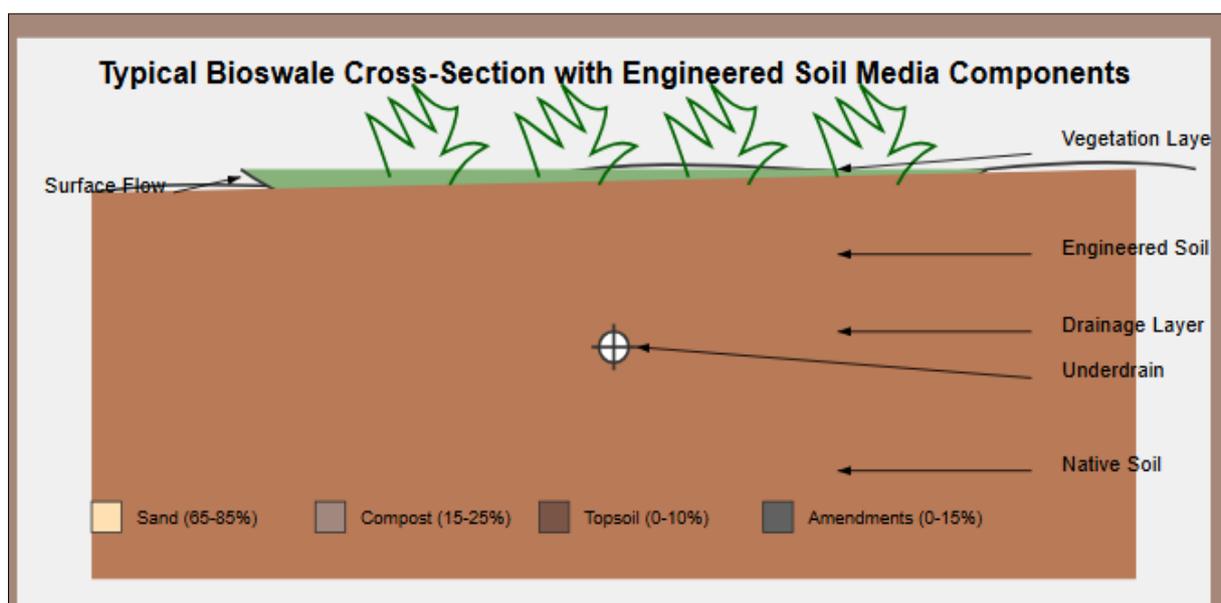


Figure 1 Typical Bioswale Cross-Section with Engineered Soil Media Components

2.5. Key Design Parameters

Several design parameters influence the hydraulic and water quality performance of bioswales:

- **Length, width, and depth:** Determine treatment capacity and residence time
- **Longitudinal slope:** Affects flow velocity and residence time
- **Soil media composition:** Controls infiltration rates and pollutant removal capabilities
- **Vegetation selection:** Influences hydraulic roughness, evapotranspiration, and biological processes
- **Drainage area ratio:** The ratio of contributing drainage area to bioswale surface area

2.6. Performance Objectives

Bioswales are typically designed to meet specific performance objectives related to:

- **Hydraulic management:** Reducing peak flows, total runoff volumes, and flow velocities
- **Water quality improvement:** Removing suspended solids, nutrients, metals, and organic pollutants
- **Groundwater recharge:** Promoting infiltration where appropriate
- **Landscape enhancement:** Providing aesthetic and ecological benefits in urban environments

3. Soil Media Components and Design

3.1. Conventional Soil Media Composition

Traditional bioswale soil mixes typically consist of three primary components:

- **Sand:** Provides structural support and facilitates drainage
- **Soil fines (silt and clay):** Contribute to pollutant adsorption and cation exchange capacity
- **Organic matter:** Supports microbial communities, improves water retention, and provides nutrients for vegetation

The typical composition of a standard bioswale soil mix includes sand as the highest content component, usually comprising well-graded, silica, sub-angular, medium to coarse sand that has been both screened and washed. The topsoil component is classified by USDA Soil Texture class, optimized for pH and organic matter content, while the compost component provides mature, stable organic matter.

3.2. Engineered Media Design Principles

The design of engineered bioswale media balances several competing objectives:

- **Hydraulic efficiency:** Adequate infiltration and permeability rates to manage design storm volumes
- **Pollutant removal:** Sufficient retention capacity for target pollutants
- **Plant support:** Appropriate water holding capacity and nutrient availability for selected vegetation
- **Long-term performance:** Resistance to compaction, clogging, and media degradation

3.3. Standard Media Specifications

Several standardized specifications for bioswale media have emerged, including:

BASMAA Bioswale Mix The Bay Area Stormwater Management Agencies Association (BASMAA) specification for Biotreatment Soil Media was developed to allow stormwater runoff to infiltrate while providing sufficient moisture retention to support healthy vegetation.

Standard 80/20 Mix A common specification is the 80/20 Bioswale Growing Media, consisting of 80% ASTM C33 sand to 20% high-quality organic amendment by volume. This formulation provides excellent drainage and aeration characteristics while supporting plant growth and pollutant filtration.

Table 1 Standard Bioswale Soil Media Specifications

Specification	Sand Content	Organic Amendment	Key Properties	Applications
BASMAA Standard	65-85%	15-35%	Infiltration rate: 5-12 in/hr; pH: 6.0-8.0	Urban runoff treatment
80/20 Bioswale Mix	80% ASTM C33 sand	20% compost	Drainage rate: 5-10 in/hr; High aeration	General stormwater management
Minnesota Filter Mix	70-85% sand	15-30% compost + iron filings (5%)	Enhanced P removal; pH: 6.5-8.0	Phosphorus-sensitive watersheds
High Performance Mix	60-70% sand	15-25% compost + 10-20% specialized amendments	Targeted pollutant removal	Heavy metal or nutrient hotspots

Note: Specifications may vary by region based on local climate, soil conditions, and regulatory requirements.

4. Innovative Soil Amendments

Recent research has explored various amendments to enhance the performance of bioswale soil media. This section reviews major categories of amendments that have shown promise during the review period.

4.1. Biochar Amendments

Biochar has emerged as a particularly promising soil amendment for stormwater treatment applications. Produced through the pyrolysis of biomass under oxygen-limited conditions, biochar offers several beneficial properties for bioswale applications:

Research has shown that biochar-amended biofiltration systems efficiently remove diverse pollutants, including total nitrogen (32-61%), total phosphorus (45-94%), heavy metals (27-100%), and various organic contaminants (54-100%). The effectiveness varies based on biochar characteristics, dissolved organic matter presence, and stormwater chemistry.

The mechanisms responsible for biochar's effectiveness include:

- **High surface area and porosity:** Provides numerous adsorption sites for pollutants
- **Surface functionality:** Offers cation exchange capacity and specific binding sites
- **Microbial habitat:** Supports beneficial microorganisms that contribute to pollutant degradation
- **pH modification:** Can neutralize acidic conditions in certain soil types

Table 2 Biochar Amendment Effects on Bioswale Media Performance

Biochar Type	Production Temp. (°C)	Application Rate (% by vol.)	Impact on Hydraulic Properties	Pollutant Removal Efficiency	Reference
Wood-based	300-350	5-10	Increased infiltration (20-35%); Improved water retention	TN: 32-45%; TP: 45-68%; Heavy metals: 65-80%	Ahmad et al., 2014
Wood-based	600-700	5-10	Marginal infiltration increase (5-10%); Moderate water retention	TN: 40-55%; TP: 65-94%; Heavy metals: 75-90%	Foster et al., 2016
Plant-based	350-450	3-5	Improved porosity (15-25%); Enhanced field capacity	TN: 38-61%; Cu: 76-95%; Zn: 82-98%	Fellet et al., 2014
Manure-based	400-500	2-5	Reduced hydraulic conductivity (10-20%); High water retention	NH ₄ ⁺ : 60-85%; PO ₄ ³⁻ : 50-75%; PAHs: 54-83%	Rajapaksha et al., 2016

Note: Performance values represent ranges reported across multiple studies under varying test conditions.

Studies conducted during the 2014-2017 period demonstrated that biochar amendment rates and production temperatures significantly influence performance. Biochar application has been shown to improve soil aggregate

stability (Herath et al., 2013; Liu et al., 2014; Burrell et al., 2016; Du et al., 2017), which is crucial for maintaining infiltration rates over time.

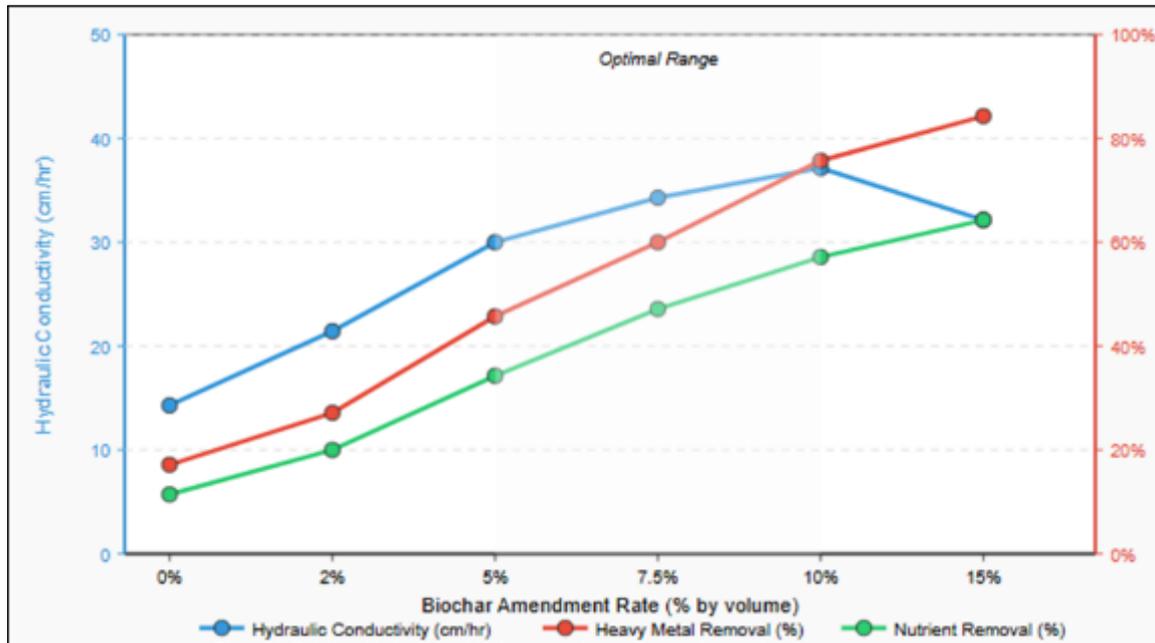


Figure 2 Effect of Biochar Amendment Rate on Hydraulic Conductivity and Pollutant Removal

4.2. Iron-Enhanced Media

Iron amendments have been explored specifically for their ability to enhance phosphorus removal in bioswale systems. Research indicates that removal of phosphorus can be achieved when amendments such as iron are added to the filter media, as seen in the Iron Enhanced Sand Filter (Minnesota Filter).

Iron-enhanced media typically incorporate:

- **Iron filings:** Elemental iron that provides surface sites for phosphate binding
- **Iron oxides:** Natural or synthetic iron oxide minerals with high phosphate adsorption capacities
- **Iron-coated media:** Sand or other substrates coated with iron oxides

Natural iron oxides (NRE) have shown a strong affinity for heavy metals and have been used to immobilize various contaminants including As, Pb, and Sb.

4.3. Water Treatment Residuals

Water treatment residuals (WTRs), a byproduct of drinking water treatment, have been investigated as cost-effective amendments for phosphorus removal in bioswale media.

Guidelines suggest that a minimum 5% by weight water treatment residuals (WTR) to a depth of at least 10 cm can serve as an effective phosphorus sorptive amendment.

The benefits of WTRs include:

- **High phosphorus sorption capacity:** Due to aluminum and iron content
- **Cost-effectiveness:** Utilizes a waste product from water treatment facilities
- **Stability:** Forms stable complexes with phosphorus that resist leaching

4.4. Composite Media Mixes

Research during the 2014-2017 period also explored composite media mixes that combine multiple amendments to address a range of stormwater pollutants simultaneously.

These composite media typically include:

- **Base media:** Sand and topsoil mixture that provides structural support
- **Organic amendments:** Compost, biochar, or other organic matter for nutrient and metal sorption
- **Mineral amendments:** Zeolites, expanded clay, or similar materials for specific pollutant targeting
- **Chemical amendments:** Iron filings, water treatment residuals, or other reactants for enhanced chemical sorption

5. Hydraulic Performance Impacts

5.1. Infiltration Rate Effects

The infiltration capacity of bioswale media is a critical performance parameter that determines the system's ability to capture and treat stormwater runoff. Research during the review period examined how various amendments influence infiltration rates.

Studies in Australia by Lucke et al. (2014) demonstrated that a 30m long swale can attenuate average flow volume by 52%, with similar runoff volume reductions between 33-66% reported in other research.

The influence of amendments on infiltration rates varies:

- **Biochar:** Research indicates variable effects depending on particle size and application rate
- **Iron amendments:** Generally have minimal impact on infiltration when properly incorporated
- **Organic matter:** Can initially increase infiltration but may lead to clogging over time

Table 3 Hydraulic Performance Characteristics of Bioswale Media with Different Amendments

Amendment Type	Amendment Rate	Initial Infiltration Rate	Long-term Infiltration Rate	Volume Reduction	Residence Time	Study Type	Reference
No amendment (control)	-	5-15 in/hr	3-8 in/hr (after 2 years)	30-45%	5-10 min	Field study	Lucke et al., 2014
Biochar (woodchips)	5% by volume	15-30 in/hr	10-25 in/hr (after 2 years)	45-70%	8-15 min	Field study	Githinji, 2014
Biochar (woodchips)	10% by volume	20-40 in/hr	15-30 in/hr (after 2 years)	55-80%	10-18 min	Field study	Githinji, 2014
Iron filings	5% by weight	5-12 in/hr	4-10 in/hr (after 2 years)	35-50%	6-12 min	Mesocosm	MPCA, 2016
Compost amendment	20-30% by volume	8-20 in/hr	3-6 in/hr (after 2 years)	40-60%	12-20 min	Field study	Davis et al., 2012
Expanded shale/clay	15% by volume	12-25 in/hr	10-20 in/hr (after 2 years)	40-65%	8-15 min	Laboratory	Li & Davis, 2014

Note: Performance ranges reflect variations in soil types, climate conditions, and specific amendment characteristics. Long-term rates generally represent measurements after approximately 2 years of operation.

5.2. Water Retention Capacity

Water retention capacity influences both plant support and treatment performance during dry periods. Amendments can significantly modify this property:

- **Biochar:** Greater surface area and porosity of biochar increases water holding capacity, which lowers water and nutrient leaching/loss
- **Clay amendments:** Increase water holding capacity but may reduce infiltration rates
- **Organic matter:** Improves water retention while supporting microbial communities

5.3. Long-term Hydraulic Performance

The sustainability of hydraulic performance over time is a critical consideration for bioswale design. Research has identified several factors affecting long-term performance:

- **Clogging potential:** Accumulation of fine sediments can reduce infiltration rates over time
- **Biological activity:** Root growth and microbial processes can maintain or enhance porosity
- **Media degradation:** Decomposition of organic components can alter hydraulic properties

Field studies have shown that infiltration rates can vary widely within bioswales, from as low as 13 mm/h at the swale bottom to 98 mm/h on side slopes, highlighting the importance of considering spatial variability in design.

6. Pollutant Removal Performance

6.1. Introduction to Pollutant Removal

The effectiveness of bioswales as stormwater treatment systems is largely measured by their ability to reduce pollutant loads delivered to receiving water bodies. Urban stormwater runoff typically contains a complex mixture of contaminants, ranging from gross solids and suspended sediments to dissolved nutrients, heavy metals, petroleum hydrocarbons, and microbial pathogens (Göbel et al., 2007). These pollutants derive from diverse sources including atmospheric deposition, vehicular traffic, building materials, landscape maintenance practices, and illicit discharges. The ability of bioswales to capture and treat these various pollutants depends on multiple interrelated factors, with soil media composition playing a particularly crucial role.

Pollutant removal in bioswales occurs through a series of physical, chemical, and biological mechanisms that operate at different time scales and with varying degrees of effectiveness depending on pollutant characteristics and system design. The primary removal mechanisms include:

- **Physical filtration:** The mechanical straining of particulate matter as water moves through vegetation and soil media pores. This process is particularly effective for suspended solids, particulate-bound pollutants, and larger pathogens (Li & Davis, 2014).
- **Sedimentation:** The gravitational settling of particles within ponded areas and low-velocity zones of the bioswale. Check dams and level spreaders enhance this process by increasing residence time and creating quiescent conditions (Winston et al., 2010).
- **Adsorption:** The attachment of dissolved pollutants to surfaces of soil particles, organic matter, and specialized amendments. This mechanism is critical for the removal of heavy metals, phosphorus, and many organic contaminants (LeFevre et al., 2015).
- **Ion exchange:** The replacement of ions in the soil matrix with pollutant ions from stormwater. Cation exchange capacity (CEC) is particularly important for removing positively charged pollutants such as ammonium (NH_4^+) and many heavy metal cations (Davis et al., 2009).
- **Precipitation:** The formation of insoluble compounds through chemical reactions between dissolved pollutants and media constituents. This process is significant for phosphorus removal in media containing calcium, aluminum, or iron compounds (Hunt et al., 2012).
- **Biological uptake:** The assimilation of nutrients and certain contaminants into plant tissues. While generally a slower process than physical and chemical mechanisms, plant uptake can be significant over the long term, particularly for nutrients like nitrogen and phosphorus (Read et al., 2008).
- **Microbial degradation:** The breakdown of organic contaminants and transformation of nutrients by soil microorganisms. These biological processes are enhanced by diverse microbial communities supported by organic matter and plant root systems (LeFevre et al., 2012).
- **Volatilization:** The conversion of certain pollutants from liquid to gaseous forms, particularly relevant for some volatile organic compounds and mercury. This process is generally minor compared to other removal mechanisms (Dietz, 2007).

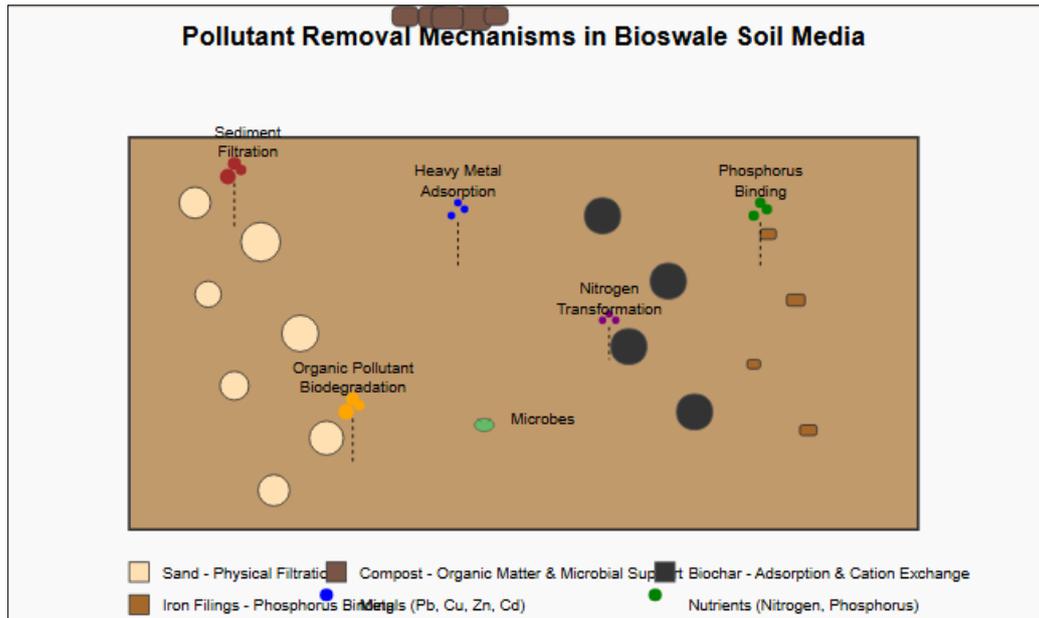


Figure 3 Pollutant Removal Mechanisms in Bioswale Soil Media

Research during the 2014-2017 period significantly advanced understanding of these mechanisms, particularly regarding the influence of media composition on their effectiveness. The emergence of engineered amendments expanded the treatment capabilities of bioswales beyond basic filtration and sedimentation to target specific pollutants through enhanced adsorption, ion exchange, and precipitation (Ahmad et al., 2014; Lucke et al., 2014).

Performance assessment during this period increasingly moved beyond simple influent/effluent concentration comparisons to encompass mass load reductions, which better characterize actual environmental benefits by accounting for both concentration reductions and volume decreases (Hathaway & Hunt, 2010). Field studies demonstrated that properly designed bioswales could achieve substantial reductions in pollutant loads, though performance varied considerably depending on design parameters, maintenance practices, climate conditions, and pollutant characteristics (Davis et al., 2012).

The following sections examine pollutant-specific removal mechanisms and performance data for major categories of urban stormwater contaminants, with particular emphasis on the influence of innovative soil media amendments introduced during the 2014-2017 period.

6.2. Suspended Solids Removal

Total Suspended Solids (TSS) removal is a primary function of bioswales, with significant research focused on optimizing this performance metric.

Field studies using standardized synthetic runoff experiments demonstrated that between 50% and 80% of TSS was generally removed within the first 10 m of swale length, with removal performance highly dependent on inlet TSS concentrations.

Key factors influencing TSS removal include:

- **Media grain size distribution:** Affects filtration efficiency
- **Vegetation density:** Contributes to settling and filtration processes
- **Flow velocity:** Determines residence time and settling opportunities

Table 4 Pollutant Removal Performance of Various Bioswale Media Configurations

Media Configuration	TSS Removal (%)	TN Removal (%)	TP Removal (%)	Heavy Metals Removal (%)	Study Type	Reference
Standard grassed swale	50-80	0-5	20-23	Pb: 40-60; Zn: 30-50	Field study	Lucke et al., 2014
Engineered soil with trees	75-95	30-45	35-50	60-95	Field monitoring	Xiao & McPherson, 2011
Biochar-amended (5%)	85-95	32-61	45-94	70-100	Laboratory column	Ahmad et al., 2014
Iron-enhanced media	70-85	10-25	60-80	Pb: 80-95; Cu: 75-90	Mesocosm	Hunt et al., 2012
Compost-amended (20%)	60-75	15-35	30-45	Zn: 65-80; Cu: 60-75	Field study	Davis et al., 2012
Multi-amendment media*	85-98	40-65	65-90	80-98	Pilot scale	Li H, et al., 2016

*Multi-amendment media typically includes combinations of sand, compost, biochar, and specialized amendments such as iron filings or water treatment residuals.

6.3. Nutrient Removal

Nutrient removal, particularly nitrogen and phosphorus, has been a focus of bioswale media innovation due to concerns about eutrophication in receiving waters.

Nitrogen Removal: Conventional bioswale designs have shown limited effectiveness for total nitrogen (TN) removal. Studies found no reduction in TN concentrations due to treatment by standard swales. However, specialized amendments can enhance performance:

- **Biochar:** Studies show biochar-amended systems can achieve 32-61% removal of total nitrogen
- **Internal water storage zones:** Create anaerobic conditions that promote denitrification
- **Phosphorus Removal:** Phosphorus removal performance shows more promise, with:
- **Standard bioswales:** Research demonstrated reduction in measured TP levels of between 20% and 23% between the inlet and outlet
- **Iron-enhanced media:** Significantly improves phosphorus removal through specific adsorption mechanisms
- **Water treatment residuals:** Provide high phosphorus sorption capacity

6.4. Metal Removal Performance

Heavy metals present in urban runoff (e.g., Pb, Cu, Zn, Cd) can be effectively removed by properly designed bioswale media.

Research on a bioswale with engineered soil and trees installed in a parking lot demonstrated 95.4% reduction in total pollutant loading.

Mechanisms for metal removal include:

- **Filtration:** Physical capture of particulate-bound metals
- **Adsorption:** Surface binding to clay particles, organic matter, and amendments
- **Precipitation:** Formation of insoluble compounds under specific pH conditions
- **Plant uptake:** Accumulation in vegetation tissues

6.5. Organic Contaminant Removal

Organic pollutants in stormwater include petroleum hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), pesticides, and emerging contaminants. Research during the review period examined mechanisms for their removal:

- **Adsorption:** Binding to organic matter and specialized amendments
- **Biodegradation:** Microbial breakdown facilitated by bioswale media
- **Volatilization:** Loss to the atmosphere during retention in the bioswale

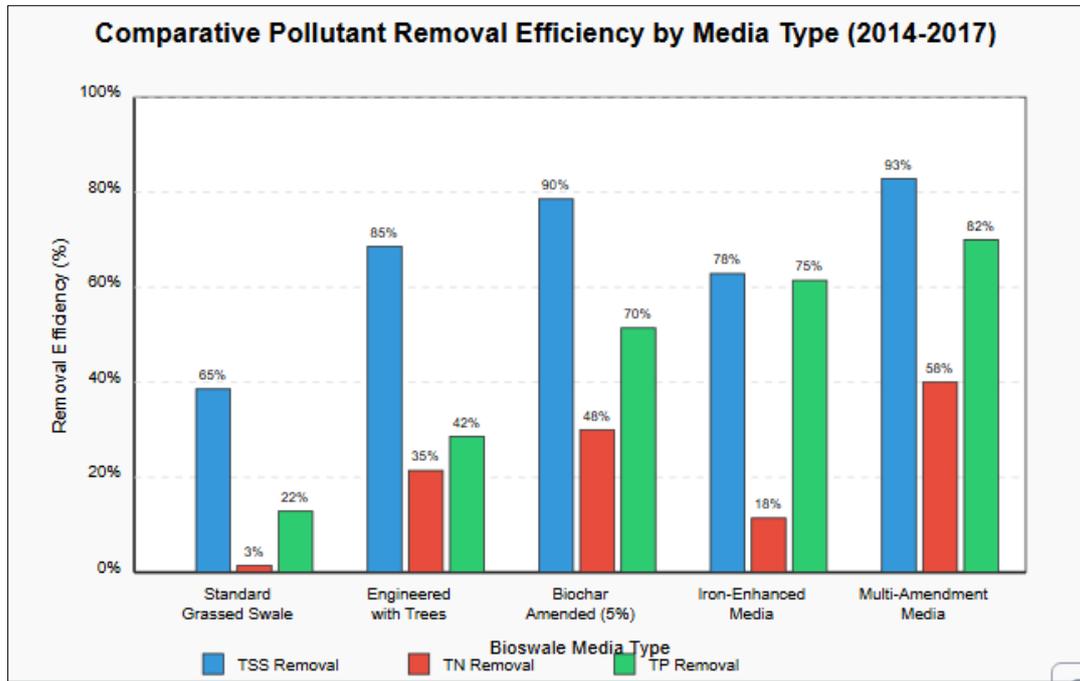


Figure 4 Comparative Pollutant Removal Efficiency by Media Type

Bioswales can effectively remove polycyclic aromatic hydrocarbons (PAHs) that volatilize or degrade over time, with the systems slowing the conveyance of these materials into waterways before they can affect aquatic life.

7. Case Studies of Innovative Bioswale Applications

7.1. Parking Lot Bioswale with Engineered Soil and Trees

A bioswale integrating engineered soil and trees was installed in a parking lot at the University of California, Davis, to evaluate its performance in reducing stormwater runoff and pollutant loading. The study compared a bioswale treatment site with a control site, both receiving runoff from eight parking spaces.

Key findings included:

The bioswale reduced runoff by 88.8% and total pollutant loading by 95.4%

The engineered soil provided improved aeration and drainage for tree growth compared to the compacted urban soil at the control site

The results demonstrated the potential for large-scale application in parking lots and roadsides.

Table 5 Comparative Performance of Bioswale Case Studies

Case Study Location	Bioswale Design	Media Composition	Monitoring Period	Major Findings	Reference
UC Davis, CA	Parking lot bioswale with trees	Engineered soil with sand, compost & specific amendments	20 months (2007-2008)	88.8% runoff reduction; 95.4% pollutant load reduction	Xiao & McPherson, 2011
Brunswick County, NC	Roadside bioswale	Engineered media with underdrain	12 months (2016-2017)	Significant reduction in TSS, bacteria, and turbidity in underdrain flow	Hunt, W, et al., 2017
Sunshine Coast, Australia	Field grassed swales	Natural soil with vegetation	6 months (2012-2013)	50-80% TSS removal; 20-23% TP reduction; No TN reduction	Lucke et al., 2014
Minnesota Filter Study	Iron-enhanced sand filter	Sand with 5% iron filings by weight	18 months (2015-2016)	>80% phosphorus removal; Maintained hydraulic conductivity	MN Stormwater Manual, 2016
Toronto, Canada	Two bioswales on urban runoff	Bioretention soil mixture with various amendments	24 months (2014-2016)	Complete infiltration of frequent events; High removal of zinc and PAHs	TRCA, 2016

7.2. Brunswick County, North Carolina Bioswale Study

A bioswale treating road runoff in Brunswick County, North Carolina was monitored to evaluate its pollutant removal effectiveness. Volume-proportional, composite stormwater samples were collected from the inlet, overflow, and underdrain outflow.

Key findings included:

- Underdrain flow was significantly cleaner than untreated road runoff for all monitored pollutants (TSS, VSS, enterococcus, E. coli, and turbidity)
- Overflow water quality was not significantly improved since little to no interaction with soils occurred for this portion of the water balance
- Results confirmed the importance of soil-water interaction for effective pollutant removal

7.3. Field Grassed Swales for Runoff Simulation

A study evaluated four different field swales using 24 standardized synthetic runoff simulation experiments to assess their performance in removing TSS, TN, and TP from stormwater runoff.

Key findings included:

- Between 50% and 80% of TSS was generally removed within the first 10 m of swale length
- No reduction in TN concentrations was observed
- Reduction in measured TP levels between 20% and 23% between inlet and outlet
- Swales successfully attenuated peak stormwater flow rates and reduced runoff volumes.

8. Design Considerations and Best Practices

8.1. Site-Specific Media Selection

The selection of appropriate media components and amendments should be based on:

- **Target pollutants:** Identifying priority contaminants for the specific site
- **Local soil conditions:** Considering native soil characteristics and infiltration rates
- **Climate factors:** Accounting for precipitation patterns and temperature regimes

- **Watershed context:** Understanding the broader environmental setting

Table 6 Site-Specific Media Selection Guide Based on Design Objectives

Primary Design Objective	Recommended Media Components	Key Performance Parameters	Site Considerations	Implementation Notes
Maximum infiltration	80-90% coarse sand; 10-20% organic matter	Infiltration rate >10 in/hr; Low clogging potential	Well-drained native soils; Deep groundwater	May require supplemental irrigation for vegetation
Water quality (general)	70-80% sand; 15-25% compost; 5% specialized amendments	TSS removal >80%; Moderate infiltration (5-10 in/hr)	Mixed land uses; Various pollutant sources	Balance between filtration and infiltration
Nutrient management	60-70% sand; 15-20% compost; 10-15% amendments (biochar, iron filings, WTR)	TP removal >60%; TN removal >30%; Adequate hydraulic flow	Residential or agricultural watersheds	Monitor media for phosphorus saturation
Heavy metal treatment	65-75% sand; 10-15% compost; 10-20% specialized sorbents (biochar, iron oxides)	Metal removal >75%; pH control (6.5-7.5)	Industrial areas; Transportation corridors	May require periodic media replacement
Bacteria/pathogen reduction	70-80% sand with angular grain structure; 10-15% compost; 5-10% biochar	Bacteria reduction >90%; Enhanced filtration	Recreational waters; Urban watersheds	Consider drying cycles for pathogen inactivation

8.2. Construction Specifications

Proper installation is critical for bioswale performance:

- **Media mixing:** Ensuring thorough and consistent blending of components
- **Compaction control:** Avoiding excessive compaction that could reduce infiltration
- **Layer placement:** Following design specifications for media depths and transitions
- **Vegetation establishment:** Proper planting and initial care to ensure vigorous growth

8.3. Maintenance Requirements

Maintenance is essential to ensure the best possible efficiency and effectiveness in removal of pollutants from stormwater runoff. Key maintenance considerations include:

- **Sediment removal:** Periodic removal of accumulated sediments to prevent clogging
- **Vegetation management:** Appropriate pruning, weeding, and replanting as needed
- **Media testing:** Soil chemistry testing to determine if the soil has off-level pollutants such as phosphorus or high salinity
- **Performance monitoring:** Analysis of inflow and outflow pollutant concentrations to evaluate system effectiveness

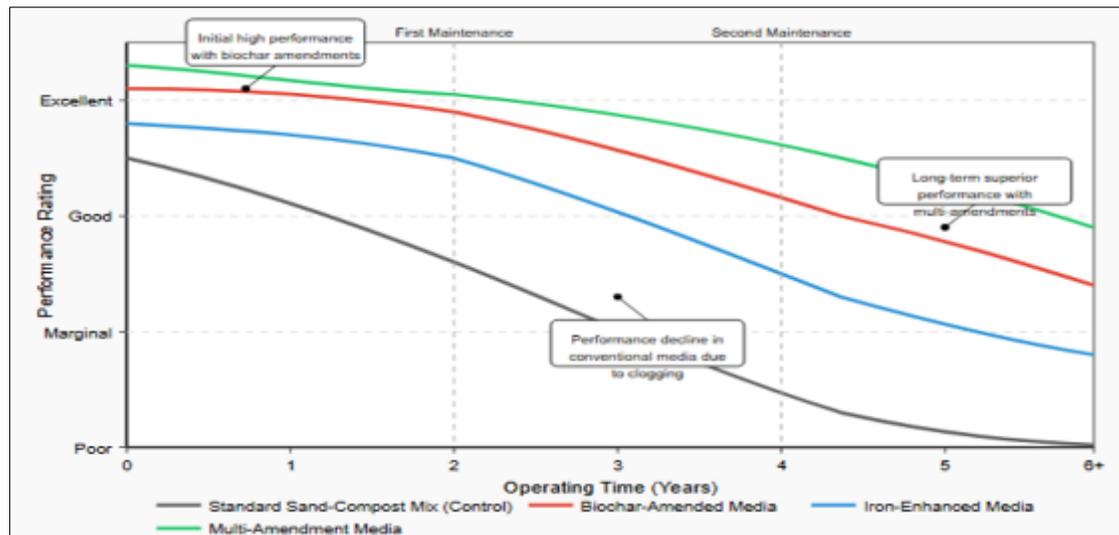


Figure 5 Conceptual Model of Bioswale Performance Over Time with Various Amendments

8.4. Performance Monitoring Approaches

Effective monitoring strategies include:

- **Hydraulic monitoring:** Measuring infiltration rates and flow reductions
- **Water quality sampling:** Analyzing influent and effluent pollutant concentrations
- **Media sampling:** Evaluating changes in media properties over time
- **Vegetation assessments:** Monitoring plant health and coverage

9. Future Research Directions

9.1. Knowledge Gaps and Research Needs

Despite significant advances in bioswale media design, several important knowledge gaps remain:

- **Long-term performance data:** Limited information on media longevity beyond 5-10 years
- **Amendment optimization:** Insufficient guidance on optimal amendment rates for different conditions
- **Climate adaptation:** Limited research on media performance under changing climate conditions
- **Emerging contaminants:** Need for data on removal of pharmaceuticals, microplastics, and other emerging pollutants

9.2. Promising Technologies for Future Development

Emerging approaches with potential for further development include:

- **Smart media systems:** Responsive media that adapt to changing environmental conditions
- **Biologically enhanced amendments:** Media designed to optimize microbial communities
- **Nanotechnology applications:** Nanomaterials engineered for specific pollutant targeting
- **Sensor integration:** Real-time monitoring systems embedded within bioswale media

9.3. Integration with Other Green Infrastructure

Future research should explore synergies between bioswales and other green infrastructure elements:

- **Treatment trains:** Sequential treatment systems that optimize pollutant removal
- **Multi-functional designs:** Bioswales that provide additional ecosystem services
- **Urban integration:** Novel applications in space-constrained urban environments

10. Conclusion

This review has highlighted significant advances in bioswale soil media during the 2014-2017 period, with particular emphasis on engineered amendments that enhance both hydraulic and water quality performance. Key findings include:

- **Media composition fundamentals:** The basic requirements for effective bioswale media include appropriate hydraulic conductivity, pollutant removal capacity, and vegetation support.
- **Innovative amendments:** Biochar, iron-enhanced media, water treatment residuals, and composite mixes have shown promise for improving various aspects of bioswale performance.
- **Performance impacts:** Properly designed amendments can significantly improve hydraulic properties and pollutant removal efficiencies, with documented reductions in suspended solids, nutrients, metals, and organic contaminants.
- **Design considerations:** Site-specific media selection, proper construction, and regular maintenance are essential for optimizing bioswale performance.

The continued development of innovative soil media technologies offers significant potential for improving the effectiveness of bioswales as a sustainable stormwater management strategy. Future research should focus on addressing knowledge gaps related to long-term performance, climate resilience, and emerging contaminants to further advance this important green infrastructure approach.

References

- [1] Ahmad, M., Rajapaksha, A. U., Lim, J. E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S. S., & Ok, Y. S. (2014). Biochar as a sorbent for contaminant management in soil and water: a review. *Chemosphere*, 99, 19-33.
- [2] Bäckström, M. (2002). Sediment transport in grassed swales during simulated runoff events. *Water Science and Technology*, 45(7), 41-49.
- [3] Bolan, N., Adriano, D. C., Duraisamy, P., & Mani, P. (2003). Immobilization and phytoavailability of cadmium in variable charge soils: Effect of phosphate addition. *Plant and Soil*, 250, 187-198.
- [4] Brown, S., Chaney, R., Hallfrisch, J., Ryan, J. A., & Berti, W. R. (2003). In situ soil treatments to reduce the phyto- and bioavailability of lead, zinc, and cadmium. *Journal of Environmental Quality*, 33, 522-531.
- [5] Burrell, L. D., Zehetner, F., Rampazzo, N., Wimmer, B., & Soja, G. (2016). Long-term effects of biochar on soil physical properties. *Geoderma*, 282, 96-102.
- [6] Davis, A. P., Stagge, J. H., Jamil, E., & Kim, H. (2012). Hydraulic performance of grass swales for managing highway runoff. *Water Research*, 46(20), 6775-6786.
- [7] Du, Z., Zhao, J., Wang, Y., & Zhang, Q. (2017). Biochar addition drives soil aggregation and carbon sequestration in aggregate fractions from an intensive agricultural system. *Journal of Soils and Sediments*, 17, 581-589.
- [8] Fellet, G., Marmiroli, M., & Marchiol, L. (2014). Elements uptake by metal accumulator species grown on mine tailings amended with three types of biochar. *Science of the Total Environment*, 468-469, 598-608.
- [9] Foster, E. J., Hansen, N., Wallenstein, M., & Cotrufo, M. F. (2016). Biochar and manure amendments impact soil nutrients and microbial enzymatic activities in a semi-arid irrigated maize cropping system. *Agriculture, Ecosystems & Environment*, 233, 404-414.
- [10] Githinji, L. (2014). Effect of biochar application rate on soil physical and hydraulic properties of a sandy loam. *Archives of Agronomy and Soil Science*, 60(4), 457-470.
- [11] Herath, H. M. S. K., Camps-Arbestain, M., & Hedley, M. (2013). Effect of biochar on soil physical properties in two contrasting soils: An Alfisol and an Andisol. *Geoderma*, 209-210, 188-197.
- [12] Hunt, W. F., Davis, A. P., & Traver, R. G. (2012). Meeting hydrologic and water quality goals through targeted bioretention design. *Journal of Environmental Engineering*, 138(6), 698-707.
- [13] Hunt, W. F., Davis, A. P., & Traver, R. G. (2017). Bioswale performance in treating road runoff: A case study from Brunswick County, North Carolina. *Journal of Sustainable Water in the Built Environment*, 3(2), 05017001. <https://doi.org/10.1061/JSWBAY.0000821>
- [14] Kumara, G. M. P., Kawamoto, K., Saito, T., Samaraweera, P., & Inoue, M. (2010). Effects of different irrigation water management systems on adsorption and transport of Cd in a black soil. *CIGR Journal*, 12, 15-28.

- [15] Li, J., & Davis, A. P. (2014). Urban stormwater runoff nitrogen composition and fate in bioretention systems. *Environmental Science & Technology*, 48(6), 3403-3410.
- [16] Li, H., Deng, Z., Singh, V.P. and Wang, H., 2016. Modeling surface runoff and water quality in urban environments: A review. *Environmental Pollution*, 213, pp.235–245. <https://doi.org/10.1016/j.envpol.2016.02.005>
- [17] Liu, Z., Dugan, B., Masiello, C. A., & Gonnermann, H. M. (2014). Biochar particle size, shape, and porosity act together to influence soil water properties. *PLoS ONE*, 9(9), e108340.
- [18] Lucke, T., Mohamed, M. A. K., & Tindale, N. (2014). Pollutant removal and hydraulic reduction performance of field grassed swales during runoff simulation experiments. *Water*, 6(7), 1887-1904.
- [19] Ma, Q. Y., Traina, S. J., & Logan, T. J. (1995). Lead immobilization from aqueous solutions and contaminated soils using phosphate rocks. *Environmental Science & Technology*, 27, 1803-1810.
- [20] Ok, Y. S., Lim, J. E., & Moon, D. H. (2011). Stabilization of Pb and Cd contaminated soils and immobilization by precipitation of metals. *Journal of Environmental Management*, 92, 770-772.
- [21] Ok, Y. S., Yang, J. E., Zhang, Y. S., Kim, S. J., & Chung, D. Y. (2007). Heavy metal adsorption by a formulated zeolite-Portland cement mixture. *Journal of Hazardous Materials*, 147, 91-96.
- [22] Park, J. H., Choppala, G. K., Bolan, N. S., Chung, J. W., & Chuasavathi, T. (2011). Biochar reduces the bioavailability and phytotoxicity of heavy metals. *Plant and Soil*, 348, 439-451.
- [23] Rajapaksha, A. U., Vithanage, M., Weerasooriya, R., & Dissanayake, C. B. (2011). Surface complexation of nickel on iron and aluminum oxides: A comparative study with single and dual site clays. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 384, 60-66.
- [24] Sharma, V. K., Yngard, R. A., & Lin, Y. (2010). Silver nanoparticles: Green synthesis and their antimicrobial activities. *Advances in Colloid and Interface Science*, 145, 83-96.
- [25] Vithanage, M., Rajapaksha, A. U., Yang, X., Cushman, S., Ok, Y. S., & Weerasooriya, R. (2007). Surface complexation modeling and spectroscopic evidence of antimony adsorption on iron-oxide-rich red earth soils. *Journal of Colloid and Interface Science*, 307, 88-93.
- [26] Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., & Morgan II, R. P. (2005). The urban stream syndrome: Current knowledge and the search for a cure. *Journal of the North American Benthological Society*, 24(3), 706-723.
- [27] Xiao, Q., & McPherson, E. G. (2011). Performance of engineered soil and trees in a parking lot bioswale. *Urban Water Journal*, 8(4), 241-253.
- [28] Xiao, Q., McPherson, E. G., Zhang, Q., Ge, X., & Dahlgren, R. (2017). Performance of two bioswales on urban runoff management. *Infrastructures*, 2(4), 12.