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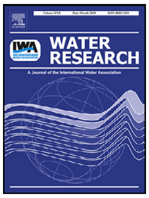

Review

Conventional and amended bioretention soil media for targeted pollutant treatment: A critical review to guide the state of the practice

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ABSTRACT

Bioretention systems are widely used green infrastructure elements that utilize engineered bioretention soil media (BSM) for stormwater capture and treatment. Conventional bioretention soil media, which typically consists of sand, sandy loam, loamy sand or topsoil amended with compost, has limited capacity to remove and may leach some stormwater pollutants. Alternative engineered amendments, both organic and inorganic, have been tested to supplement BSM. Yet, municipalities and regulatory agencies have been slow to adopt these alternative amendments into their design specifications, partly because of a lack of clear guidance on how to select the right amendment to treat a target stormwater contaminant under highly variable climatic conditions. This article aims to provide that guidance by: (1) summarizing the current design BSM specifications adopted by jurisdictions worldwide, (2) comparing the performance of conventional and amended BSM, (3) highlighting advantages and limitations of BSM amendments, and (4) identifying challenges for implementing amendments in field conditions. The analysis not only informs the research community of the barriers faced by stormwater managers in implementing BSM amendments but also provides guidelines for their adoption by interested agencies to comply with existing regulations and meet design needs. This feedback loop could catalyze further innovation in the development of sustainable stormwater treatment technologies.

1. Introduction

Urbanization fundamentally shifts the water balance, increases the rate and volume of stormwater runoff produced, and deteriorates the water quality of receiving water bodies (Walsh et al. 2005). Stormwater control measures (SCMs) have historically been designed to reduce flooding by reducing peak flow rates of runoff (Burns et al. 2012), but they have been more recently employed to reduce runoff volume (Dietz 2007, Roy et al. 2008) and improve water quality (Li and Davis 2014, Chandrasena et al. 2017, Lee et al. 2020), with the intent to augment water supply (Gee and Hunt 2016), aid in restoration of pre-development hydrology (Damodaram et al. 2010), and partially mitigate the effects of climate change (Zahmatkesh et al. 2015). Examples of green stormwater infrastructure include bioretention cells, bioswales, permeable pavements, infiltration basins and trenches, and green roofs (Dietz 2007). Among these SCMs, bioretention cells are the most commonly employed due to flexibility in their design, runoff reduction potential, water quality improvement, and potential for aesthetic enhancement of a site, advantageous features in urban areas where space may not be available to implement other types of SCMs.

Bioretention cells are planted media filters designed to capture and reduce the volume of stormwater runoff and remove pollutants via several physical and biogeochemical processes (Davis et al. 2009). These processes are, at minimum, partially influenced by the bioretention soil media (BSM) composition

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(Carpenter and Hallam 2009, Hsieh and Davis 2005, O'Neill and Davis 2010). The composition of BSM depends on the local, state, or regional design objectives and regulations, cost and availability of BSM from local sources, and its ability to serve three critical functions: support plant health, improve water quality, and rapidly infiltrate stormwater runoff (Davis et al. 2009). Though many different design "recipes" exist, BSM typically consists of sandy soil blended with an organic amendment such as compost, wood chips, bark fines, or topsoil (Wardynski and Hunt 2012). However, pollutant removal capacity of traditional BSM is low, particularly for dissolved pollutants, and they may leach pollutants into the stormwater (Ahiablame et al. 2012, Hsieh and Davis 2005, Mohanty et al. 2018, Peng et al. 2016). Therefore, there is a growing need to add amendments to improve the contaminant removal capacity of traditionally designed BSM.

Characteristics of desirable BSM amendments are: (1) low cost, (2) easily available raw materials, (3) longevity, (4) ability to support plant growth, and (5) contaminant removal capacity (Thompson et al. 2008, Hsieh and Davis 2005). Several materials, including pyrogenic carbonaceous materials such as biochar (Mohanty et al. 2018), recycled waste biomass (Sun et al. 2020), absorbents used in drinking water treatment (Xu et al. 2020), and other emerging amendments including nanoparticles (Marvin et al. 2020), have been investigated as possible amendments to conventional BSM in laboratory-scale column and small-scale pilot studies (Lim et al. 2015, Lucas and Greenway 2010, Peng et al. 2016). These media amendments show promising potential for removing chemical and microbial contaminants in bench-scale studies (Bailey et al. 1999, Bester et al. 2011, Brown et al. 2000, Chang et al. 2010, Cundy et al. 2008, Lim et al. 2015) and field conditions (Davis 2007, Passeport et al. 2009). Yet stormwater practitioners have been slow to adopt BSM amendments for several reasons: (1) high cost and low availability, (2) inconsistent pollutant removal performance, (3) uncertainty of performance in field conditions, and (4) policy and operational constraints. Regulatory agencies have jurisdiction over local, state, regional, or national standards for BSM composition, which specify allowable BSM properties and design conditions. However, they rarely incentivize the use of amendments with additional crediting for pollutant removal (e.g., MDE 2009, ODNR 2006, DDOE 2020). Regulators need third-party laboratory and field-scale data for BSM amendments to assess their effectiveness before they can be incorporated into stormwater policies (Herrera 2020).

Inconsistent design of laboratory-scale studies and a general lack of field-scale studies result in limited transferability of BSM amendment performance to bioretention design specifications. While laboratory conditions are ideal for understanding removal mechanisms and comparing performance between control and amended BSM (Carpenter and Hallam 2009, Erickson et al. 2012, Schifman et al. 2016, Cording et al. 2018), the findings are often not directly applicable for field-scale design because of regulatory control of BSM specifications, extremely variable operation of bioretention systems under temporally varied flow and complex stormwater chemistry, and reluctance of regulators to apply novel techniques. Increasing adoption of BSM amendments requires both designing laboratory studies that fully incorporate the complexities of field conditions and informing regulators of the cost and benefits of new amendments so that stormwater policies can be modified to incentivize their use.

Herein, we critically review the performance of bioretention systems to highlight specific pollutants that are not removed by the traditional BSM, compare the pollutant removal benefits of different BSM amendments, and relate their efficiency to their compositions, properties, and operating conditions. We also compare BSM media specifications in jurisdictions across the world and highlight their limitations. We then analyze and compare contaminant removal capacities of the most common media amendments and identify challenges in implementing these amendments in field settings. The analysis informs development of a framework to adopt these new BSM amendments into design standards. We intend this article to supply information on BSM amendments to optimize their use in stormwater quality improvement and inform proper crediting of amendments toward pollutant removal.

2. Bioretention cells and bioretention soil media (BSM)

2.1. Bioretention overview

A typical bioretention cell is a landscape depression backfilled with BSM and consists of a vegetated ponding zone, mulch layer, and a drainage layer of washed aggregate that can, depending on design, envelop a perforated underdrain (Fig. 1). Bioretention cells are characterized by three main components: inlet and/or outlet hydraulic controls, vegetation, and BSM. Stormwater runoff enters a bioretention cell via a curb cut, pipe, level spreader, or as sheet flow. An energy dissipator such as a forebay is often included in cells receiving concentrated inflow. The outlet configuration and properties of the BSM used in a bioretention cell dictate its hydraulic retention time. Designs which restrict underdrain flow by using an orifice or valve or which promote internal water storage (by using an upturned elbow in the underdrain) have been shown to be advantageous for runoff reduction and pollutant load mitigation, especially for nitrogen removal via denitrification (Winston et al. 2016; Dietz and Clausen 2006).

These vegetated media filters are designed to capture, reduce, and treat stormwater runoff through a variety of physical, chemical, and biological processes, including retention in pore spaces, infiltration and subsequent exfiltration, evapotranspiration, filtration, sedimentation, sorption, precipitation, oxidation/reduction, plant uptake, and biodegradation (Table 1). Standards for bioretention design, including species and density of vegetation, sizing relative to the contributing catchment, and BSM composition and depth, vary between municipalities, states, and countries. In addition to improving aesthetics, plants promote removal of suspended solids, biological uptake of contaminants including heavy metals and organic contaminants (Bratieres et al. 2008), and soil macropore formation via root growth, which in turn helps to maintain the long-term hydraulic conductivity of BSM (Jenkins et al. 2010). Bioretention vegetation must be tolerant of the unique growing conditions in BSM and moisture content in field conditions (Tirpak et al. 2018). Thus, it is critical to select BSM media that supports plant growth and increases their resilience to stressors including high salinity and low moisture.

2.2. Traditional BSM performance

Typical BSM consists of sand, silt, and clay mixed with topsoil or compost at a specified ratio to achieve a desired hydraulic conductivity. The sand fraction in traditional BSM permits rapid infiltration of stormwater, while silt, clay and the organic amendment (e.g., topsoil or compost) increase water retention for plant uptake, are critical to contaminant removal, and are blended to achieve a desired hydraulic conductivity (Hunt et al. 2012). BSM serves multiple functions related to water quality improvement, flow control, and ecosystem services (Davis et al. 2009). BSM performance depends on land use, climate, precipitation patterns, hydraulic loading ratio (i.e., ratio of contributing catchment area to bioretention surface area), and contaminant concentrations (Boehm et al., 2020). Aging of BSM under field conditions may also influence

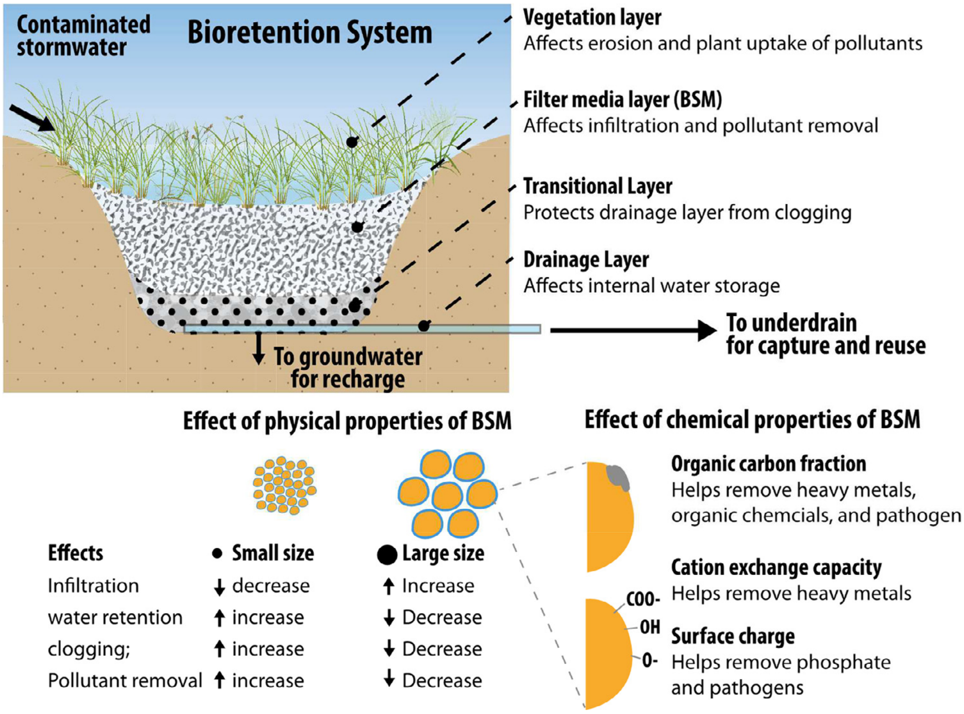

Fig. 1. Typical cross-section of a bioretention cell and effects of BSM properties on contaminant removal.

Table 1
Contaminant removal processes in bioretention cells.

Processes	Description in the context of stormwater treatment	Implication for BSM Performance	Parameters to identify favorable BSM
Infiltration	Stormwater movement to subsurface	Volume capture	Hydraulic conductivity
Sedimentation	Settling of suspended particles due to gravity	Suspended solids removal; microbial removal	Hydraulic retention time
Filtration	Straining/entrapment of particles into the interstitial spaces	Colloids removal; microbial removal	Particle size distribution
Sorption	Adsorption/absorption of dissolved pollutants to the BSM grains	P, heavy metals, trace metals, and organics removal	Absorption/absorption capacities
Attachment	Deposition of nano- and micro-scale particles onto BSM grains	Microbial removal	Hydrophobicity, surface charge
Precipitation	Removal through metal-ligand complexation and settling	P and heavy metal removal	Surface groups
Ion Exchange	Exchange of deleterious ions for ions with no adverse environmental impacts	Heavy metal removal	Cation/anion exchange capacity
Oxidation/ Reduction	Oxidation/reduction of contaminants to form benign substances or facilitate other types of removal	Organics, N, and metals	Surface groups; pH; redox potential
Biodegradation	Degradation of contaminants through microbial action	Nitrate, organics	Active biomass/g of media; pH
Phytoremediation	Plant uptake and transformation of contaminants	Trace organics, heavy metals	Plant health/species

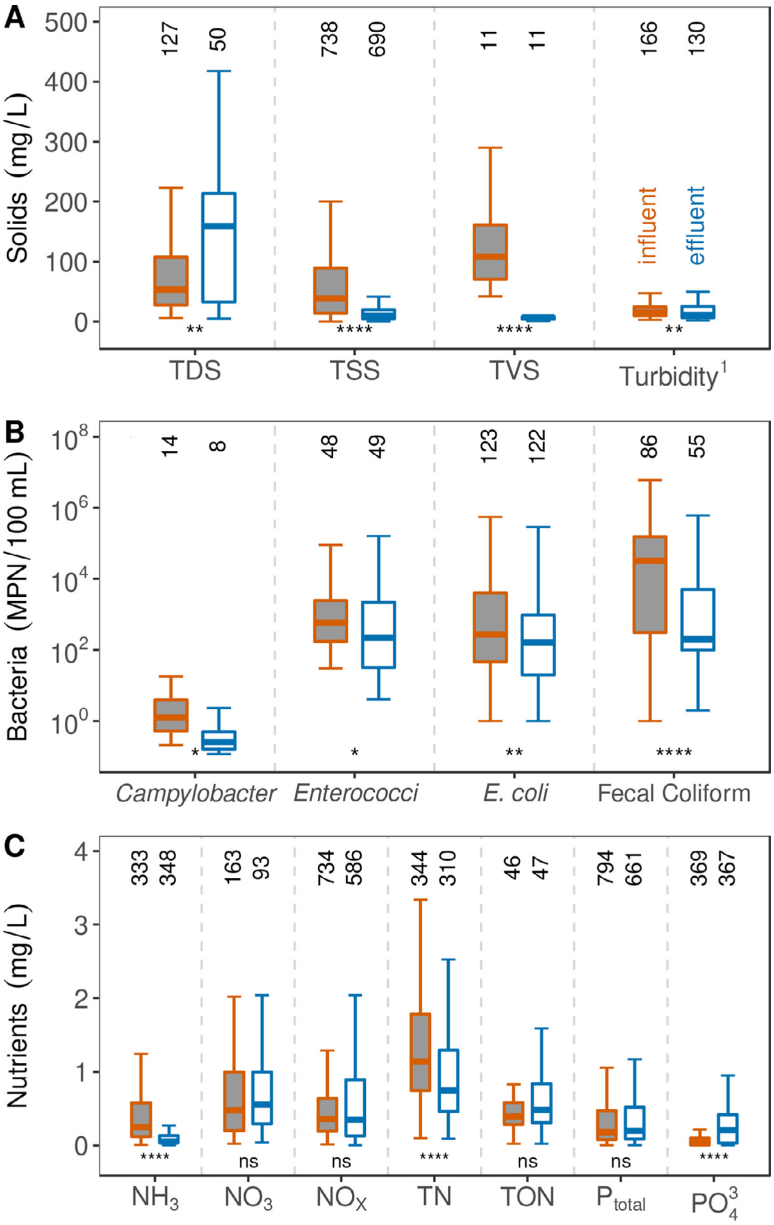

Fig. 2. Influent and effluent concentrations of pathogens, solids, and nutrients for bioretention systems in the ISBMPD (Clary et al. 2017). The number of observations included in each boxplot is presented above the figure, while statistical differences between influent and effluent concentrations, as determined by the Wilcoxon rank sum test, are indicated below each boxplot pair (ns: not significant ($p > 0.05$); *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; and ****: $p < 0.0001$). ^{1}Note: turbidity reported in NTU.

performance due to changes in physicochemical properties over time (Afrooz and Boehm, 2017). The effect of bioretention design on critical functions such as hydraulic retention time is also important for contaminant reduction (Cording et al. 2018). Differences in bioretention design features in combination with other environmental factors (e.g., climate, precipitation patterns, runoff volume and timing, and contaminant concentrations) contributes to wide variations in contaminant concentration reductions observed in field-scale bioretention systems (Manka et al. 2016, Cording et al. 2018).

Data from the International Stormwater BMP Database (ISBMPD) were analyzed to investigate the pollutant removal performance of a wide range of bioretention systems monitored under field conditions (Clary et al., 2017). Analysis of the contaminant concentrations in runoff influent to and effluent from bioretention systems in the ISBMPD demonstrates that the removal of pathogens is low and highly variable (Fig. 2). While bioretention systems are effective in removing total suspended solids (TSS) and total volatile solids (TVS), they are not effective in removing dissolved nutrients, including nitrate and phosphate (e.g., concentration significantly increased from inlet to outlet), which have critical impacts on algal blooms) (Heisler et al. 2008). While bioretention systems consistently remove total heavy metals (Fig. 3), export of dissolved heavy metals such as iron (Fe) and nickel (Ni) has been observed, indicating that the BSM can serve as a net source of these metals. These results highlight the limitations of traditional BSM in removal of particularly dissolved pollutants (Figs. 2 and 3). Thus, BSM media amendments are needed to reduce the variability in conventional BSM treatment performance and assure high removal rates for target contaminants.

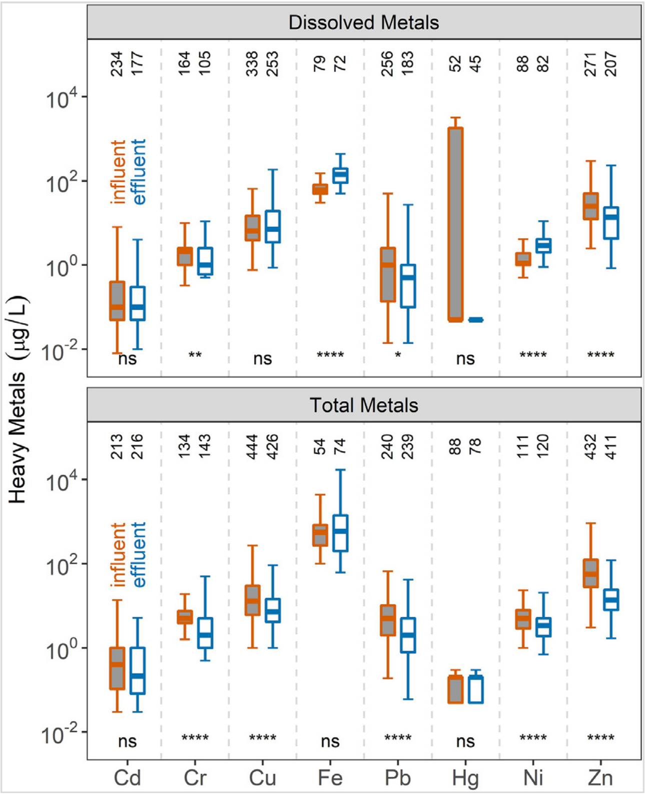

Fig. 3. Influent and effluent concentrations of total and dissolved heavy metals for bioretention systems in the ISBMPD (Clary et al. 2017). The number of observations included in each boxplot is presented above the figure, while statistical differences between influent and effluent concentrations, as determined by the Wilcoxon Rank Sum test, are indicated below each boxplot pair (ns: not significant ($p > 0.05$); *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$; and ****: $p < 0.0001$).

The variable removal capacity of bioretention systems can be attributed to a wide distribution of components specified in BSM and their ability to adsorb pollutants. The components of BSM can be classified as follows: (1) mineral fraction, (2) organic fraction, and (3) secondary amendment (Fassman-Beck et al. 2015). The mineral fraction makes up the majority of BSM and dictates the infiltration capacity of a bioretention system and the filtration of sediment or contaminated particulates ($>$ 10 μm) (Thompson et al. 2008). Based on its particle size distribution, the mineral fraction can be classified into three categories: sand (50-2000 μm), silt (2-50 μm), and clay ($<$2 μm). Relative distribution of these fractions results in a soil textural classification; BSM often falls into the loamy sand, sandy loam, or loam textural classes. A variety of BSM have been developed based on field and laboratory testing, and they often differ substantially across cities, states, and countries (e.g., MDE 2009, CRC for Water Sensitive Cities 2015, Woods-Ballard et al. 2015, MPCA 2019, PWD 2019).

The organic fraction of the BSM is critical for water holding capacity, maintaining soil structure, and supporting the health of plants and soil microbiome responsible for degradation of pollutants in a bioretention cell (Mitchell-Ayers and Kangas 2018). The OM in BSM also improves the removal of contaminants including organic contaminants and heavy metals, primarily through sorption (Mohanty et al., 2018). Biodegradation of trace organic pollutants is also increased due to the OM component of BSM (Ulrich et al., 2017b). Depending on the source, the organic amendments can sometimes leach contaminants to treated stormwater exiting the bioretention cell (Iqbal et al., 2015). To predict the leaching potential of the organic amendment, it is recommended to perform Synthetic Precipitation Leaching Procedure (SPLP) analysis (USEPA, 1994). SPLP analysis provides a benchmark to evaluate leaching potential across OM sources (e.g., compost, peat moss, bark fines, etc.). This is particularly important, given the leaching of dissolved nutrients (nitrate and phosphate) and dissolved metals reported in field studies (e.g., Fig. 2). To reduce leaching or increase removal of specific pollutants, specific amendments can be incorporated into BSM specifications, as described in Section 4.

3. Specifications for composition of BSM

3.1. BSM composition specified in design guidelines of select jurisdictions and countries

For more than two decades, the composition of BSM has evolved to provide different stormwater management functions, starting from volume reduction with limited contaminant removal to treatment of stormwater for harvesting and reuse. The first bioretention design guideline was developed in the 1990s in Prince Georges County, Maryland (County 1993), which aimed at treating the first flush of runoff using a layer of sand and potting soil planted with native grass and shrubs. Since then, this simplistic media specification has been improved to meet the challenges of comprehensive stormwater capture and treatment associated with today's LID-based approaches. Municipal, state/provincial, and national agencies provide guidance on the desirable physical and chemical soil properties of a given BSM composition. These specifications set minimum standards for soil blending facilities to achieve in a given jurisdiction. Below, we review BSM specifications from four U.S. states—Maryland, Minnesota, Ohio, and North Carolina—five municipalities—Philadelphia, PA, Washington, D.C., Sa Portland, OR in the U.S. and Toronto, Canada— and three countries – Germany, Australia, and the United Kingdom.

3.2. Physical properties in BSM specifications

Particle size distribution is the most important physical property of BSM which directly or indirectly influences other physical properties, including: surface area, bulk density, and pore size distribution. Thus, selection of BSM particle size provides a first order control for optimizing the hydraulic conductivity, maintenance frequency, and the contaminant removal capacity of a BSM mixture (Funai and Kupec 2017). An increase in median particle size typically increases the hydraulic conductivity of filter media (Kandra et al. 2014) - a desirable property to ensure treatment of a greater fraction of stormwater and reduce clogging potential. However, doing so decreases both hydraulic retention time and the effective surface area (or number of reactive sites) available for contaminant removal (Inyang et al. 2012; Mohan et al. 2014). Therefore, striking a balance between coarse and fine particles is important to optimize hydraulic conductivity; BSM specifications from several countries suggest that the soil should be well graded to maintain a desirable hydraulic retention time (Table 2).

Textural classifications outlined in regulatory specifications result in a wide range of sand (50-2000 μm; 35-90%), silt (2-50 μm; 0-55%), and clay ($<$2 μm; 0-25 %) fractions in BSM. Sand, the primary component of BSM mix, is typically specified using ASTM C33 or D422 standards (ASTM 2007, ASTM 2018). Based on textural classification, the hydraulic conductivity of BSM mixtures can greatly vary, with reported values ranging from 33 mm/hr for loamy mixtures to 160 mm/hr for primarily sand mixtures that contain 2.5% OM and loose soil (Saxton and Rawls 2009). This wide variety of BSM infiltration rates can have substantial

Table 2
Bioretention soil mixes from select jurisdictions.

Jurisdiction or Country	% Sand	% Silt	% Clay	Topsoil	%Gravel	% OM	Textural Classification	Maximum P content (mg/kg)	pH	Soluble salts	% compost (by volume)	Mix Design
Maryland	35-60%	30-55%	10-25%	0%	0%	1.5-4.0% by weight	Loamy sand, sandy loam, or loam	Not specified	5.2-7	<0.75 dS/m	4-20% (estimated)	
Washington DC	80-90%	10-20%	Min. 10%	0%	0%	3-5% by weight	Loamy sand, sandy loam, or loam	18-40 Mehlich-3 P	Not specified	Not specified	~8-20% (estimated)	Peat moss, humus, or compost as OM
Minnesota Mix A	60-70%	Not specified	Not specified	15-25%[*]	0%	15-25% by volume	Not specified	12-30 mg/kg Mehlich-3 to receive P removal credit	6-8.5	<0.75 dS/m	15-25%	OM MNDOT grade 2 compost
Minnesota Mix B	70-85%	Not specified	Not specified	0%	0%	15-30% by volume	Not specified	12-30 mg/kg Mehlich-3 to receive P removal credit	6-8.5	<0.75 dS/m	15-30%	OM MNDOT grade 2 compost
Minnesota Mix C	85-88%	8-12%		0%	0%	3-5% by volume	Not specified	12-30 mg/kg Mehlich-3 to receive P removal credit	6-8.5	<0.75 dS/m	3-5%	OM MNDOT grade 2 compost
Minnesota Mix D	50-65%	25-40% by weight		25-35%[*]	12% max (fine gravel)	2-5% by weight	Not specified	12-30 mg/kg Mehlich-3 to receive P removal credit	6-8.5	<0.75 dS/m	10-15%	OM MNDOT grade 2 compost
North Carolina	80-90%	5-10%		0%	0%	5-10% by volume	Sand or loamy sand	30 mg/kg in nutrient sensitive waters, 50 mg/kg elsewhere	Not specified	Not specified	0%	Pine bark fines specified instead of compost
Ohio	75%	Not specified	Not specified	15%[**]	0%	3-5% by weight	loamy sand	15-60 mg/kg Mehlich 3 P	5.2-8.0	<0.75 dS/m	8-20%	leaf compost, pine bark fines, mulch fines
Portland	Not specified	Not specified	Not specified	60-70%[***]	Not specified	30-40% by volume	Not specified	Not specified	6.0-8.0	Not specified	30-40% by volume	Plant derived compost only
Philadelphia	50-85%	40% max.	10% max.	0%	15% max.	3-15% by weight	Sandy loam or loamy sand	Not specified	5.8-7.1	<2 dS/m	~8-60% (estimated)	
Germany	>90%	<10% clay + silt by weight		1-3% by weight	Not specified	1-3% by weight	Fine or medium sand	Not specified	6-8	Not specified	0%	OM is topsoil
Australia	94-100%	<10% clay + silt by weight		0%	<3%	<5% by volume	Well graded sand (not a loam)	<80 mg/kg (Colwell test)	5.5-7.5	<1.2 dS/m	0%	OM is sugar cane mulch, pine chips, or pine sawdust
United Kingdom	85-100%	<10% clay + silt by weight		0%	<10%	3-5% by weight	Well graded sand	Extractable P 16-100 mg/kg	5.5-8.5	<3.3 dS/m	Not specified	
Toronto	75-97%	<10% clay + silt by weight, 3-12% clay		Not specified	Not specified	3-10% by weight	Not specified	12-40 mg/kg (Olsen method)	Sand <7, topsoil 6-8	Not specified	Not specified	OM is yard, leaf, and wood waste compost

References: Ohio Dept. of Natural Resources (ODNR) Division of Soil and Water Conservation 2014; Maryland Dept. of the Environment (MDE) 2009; District Dept. of the Enviornment (DDOE), Watershed Protection Division 2013; City of Portland 2016; Minnesota Pollution Control Agency (MPCA) 2019; North Carolina Dept. of Environmental Quality (NCDEQ) 2018; Philadelphia Water Dept. (PWD) 2019; Kluge et al. 2018; CRC 2015; Woods-Ballard et al. 2015; Credit Valley Conservation 2020.

Topsoil defined by USDA classification as:

[*] sandy loam, loamy sand, or loam;

[**] loam, silt loam, or clay loam;

[***] loamy soil or sand

effects on the quantity of water infiltrated during wet weather and the water quality of the effluent leaving the bioretention cell, particularly for dissolved pollutants. A high infiltration rate in a BSM diminishes contact time, which is critical to adsorption and biological processes responsible for dissolved pollutant removal (LeFevre et al. 2014).

Of the BSM specifications reviewed, the organic fraction in BSM may vary from 3-40% -percent by volume (Table 2). Most specifications in the U.S. explicitly designate compost as the OM source while others merely recommend the inclusion of organics in BSM mixtures (Table 2). BSM specifications in some jurisdictions include “topsoil” (ODNR 2014, MPCA 2019), for which no consistent definition exists and which may vary to a large extent texturally, thereby substantially influencing the physical and hydraulic properties of the BSM delivered to the construction site (Ballabio et al. 2016). Because of its debatable definition, the use of the term “topsoil" should be avoided in media specifications; instead, the physical properties of a BSM mix should be explicitly defined to allow media vendors and design engineers to focus on achieving a designated sand/silt/clay percentage and/or a textural classification.

Proper installation methods are also generally specified for BSM, which can be easily tested *in situ* or in a soil physical properties laboratory to ensure a desired infiltration rate is achieved. Compaction that occurs during and following installation can greatly influence infiltration rates of BSM; laboratory and field testing have demonstrated a 3 to 10-fold decrease in infiltration rates in compacted BSM compared to non-compacted trials (Pitt et al. 2004). Jurisdictions either specify that BSM should be installed without mechanical compaction (which allows stormwater to naturally consolidate the soil) (NCDEQ 2018) or using wide track or marsh track machinery to reduce the impact on newly installed BSM (MDE 2009, MPCA 2019). Specifications in Ohio suggest BSM be installed in 30 cm lifts, each soaked by water after application to promote settling (ODNR, 2014). An infiltration rate of 25-203 mm/hr is often targeted (DDOE 2013, MPCA 2019, NCDEQ 2018) to maximize infiltration of stormwater while maintaining adequate effluent water quality. Higher flow rates (2540 mm/hr) are sometimes targeted in high flow bioretention concepts but limited dissolved pollutant removal results are available todate (Smolek et al. 2018).

3.3. Chemical properties in BSM specifications

The chemical properties of BSM that affect pollutant removal include organic carbon content, hydrophobicity, cation or anion exchange capacity, surface charge, and chemical functional groups capable of interacting with specific contaminants (Muthukrishnan and Oleske 2008). These chemical properties are critical for the sorption of dissolved (and attachment of particulate) contaminants to media, degradation or transformation of contaminants over time, and release of sequestered contaminants when pore water chemistry is modified by stormwater infiltration (Tedoldi et al. 2016). Increasing the organic carbon content of BSM typically increases removal of contaminants via hydrophobic interaction (LeFevre et al., 2014). This process is responsible for removal of contaminants with low water solubility, such as polycyclic aromatic hydrocarbons (PAH) (DiBlasi et al. 2009).

Almost all BSM specifications provide some guidance on the desired chemical properties of the media mixtures (Table 2). Such guidelines may include a range of soil pH, salinity, carbon-to-nitrogen ratio (C:N), phosphorus (P), sulfate, and heavy metal content. Washed sand, which is free from wood, waste, coating, or plastics, is generally acceptable for BSM. To increase the organic carbon content, several sources/feedstocks can be added to BSM, including pine bark fines, peat moss, humus, plant-derived compost, and mulch fines (Table 2). Compost feedstock must be explicitly defined, and the compost used in BSM is required to comply with the specified Solvita Maturity Index (WERL, 1999) and other chemical properties, including OM content, moisture content, and pathogen concentration. Compost chemical properties should be evaluated to ensure that nutrient and metals leaching from the BSM will not occur (Hunt et al. 2008; Clark and Pitt 2009).

P content of BSM demands special attention due to its potential association with P leaching from a bioretention cell, particularly when manure-based composts are used in BSM (Hunt et al. 2006). Analysis of data contained within the ISBMPD showed that bioretention systems are, on average, a net source of phosphate (Fig. 2). Specifying a P content level in BSM, often measured using the Mehlich-3 Soil Phosphorous test (Mehlich 1984), is critical because it facilitates the elimination of inappropriate compost feedstocks in BSM. However, some of the BSM specifications reviewed in this study do not have an allowable limit of P content for BSM (Table 2). While Minnesota, North Carolina, Ohio, and Washington D.C. have a specified maximum P content in BSM, a wide range of values (between 12-60 mg P/kg compost) are permitted. Particularly for nutrient-sensitive receiving water, BSM Mehlich 3 P content should be limited to reduce P leaching.

The origin of the feedstock used to prepare compost, such as dairy and poultry manure and sewage sludge, can result in a wide range of P content (Sharpley and Moyer 2000, Mkhabela and Warman 2005, Casado-Vela et al. 2006). These compost feedstocks should be avoided in any concentration in BSM as their extremely high P contents are likely to result in substantial leaching based on threshold BSM soil mix concentrations (Logsdon and Sauer 2016, Jay et al. 2017). The current P-content recommendation in BSM specifications may be too broad and unlikely to result in any P reduction in BSM; Hunt et al. (2006) suggests a threshold of 15 mg/kg Mehlich-3 P for BSM to observe P removal in bioretention systems, which is at the lower end of the P-content levels recommended by the jurisdictions reviewed in this study.

In addition to the association between organic material sources and P leaching, OM in BSM containing topsoil may contribute nutrients to the stormwater (Liu et al. 2012, Hille et al. 2019). If topsoil is sourced from agricultural land, for instance during construction of a neighborhood, it may be supersaturated with P from historical fertilizer applications (Hille et al. 2019). These fields often have soil test P levels high enough to cause dissolved P to leach during rain events and are a major source contributing to dead zones, eutrophication, and harmful algal blooms in many surface waters, including the Mississippi River basin, Lake Erie, and Lake Okeechobee (Basu et al. 2010, King et al. 2017). Additionally, as OM content in BSM increases, export of nitrogen compounds released due to ammonification and subsequent nitrification, has been observed (Hunt et al. 2006, Carpenter and Hallam 2010).

4. BSM amendments

The stormwater research community has devoted significant efforts to investigate various BSM amendments to improve the hydraulic and contaminant removal performance of bioretention cells. In this section, we discuss the performance of these BSM amendments in terms of contaminant removal capacity, hydraulic performance, and plant support. Amendments are presented as percentage by mass unless otherwise specified.

4.1. Organic amendments

The performance of various organic substances, including biochar, peat moss, and coconut coir as potential BSM amendments is presented in Table 3.

Table 3
Properties of three major organic BSM amendments reported in the literature.

Amendment	Source material	C/N Ratio	Specific Surface Area (m^2/gm)	Cation exchange capacity (cmol/kg)	Surface functional groups	pH	Water holding capacity (mL/L)	Cost per cubic yard	% in BSM (by volume)	Target Pollutants
Biochar	Waste Biomass	65-110 (Blok et al. 2017)	104-350 (Afrooz and Boehm 2016, Lawrinenko and Laird 2015)	6.0-61.1 (Gaskin et al. 2008) ANC: 0.602-4.11 (Lawrinenko and Laird 2015)	Carboxylic, phenolic, lactonic, aromatic, sulfonic (Liu et al. 2015)	7.5-9.5 (Afrooz and Boehm 2016)	500-700 (Blok et al. 2017)	\$120-\$250[a]	5-30	Bacteria, organics
Peat Moss	Sphagnum Moss	48-55 (Abad et al. 2005, Tripepi 2014)	10-20 (Akinbiyi 2000, Gonzalez et al. 2016)	108-162 (Rippy and Nelson 2007)	Carboxyl, Phosphoryl, Amine, Polyphenol (Gonzalez et al. 2016)	3.7-4.4 (Chaney and Hundemann 1979, Lee et al. 2015b)	600-800 (Abad et al. 2005, Boelter 1964)	\$30-\$50[b]	5-15	Heavy metals
Coconut Coir	Coconut husk	100-190 (Tripepi 2014)	167 (Chowdhury and Fatema 2016)	40-90 (Abad et al. 2005)	Hydroxyl, alkyl, carboxyl (Etim et al. 2016, Umoren et al. 2012)	5.2-6.2 (Abad et al. 2002)	600-1400 (Abad et al. 2005, Evans et al. 1996)	\$100-\$150[c]	5-10	Metals, phosphorus

References:
[a] Herrera 2016
[b] Hinman and Curtis 2017
[c] WRA Environmental Consultants 2010

4.1.1. Biochar

Biochar is a pyrogenic carbonaceous sorbent produced via pyrolysis of biomass at elevated temperature in the absence of oxygen. Biochar characteristics may vary greatly depending on the properties of the feedstock and the production process, which in turn can also affect their contaminant removal capacity (Xie et al., 2015). Biochar removes contaminants through a variety of mechanisms, including pore-filling, partitioning or adsorption, hydrophobic interaction, electrostatic interaction, and aromatic pi- and cation-pi interaction (Inyang et al. 2016, Liu et al. 2015). Relatively low production cost, high specific surface area, good absorption capability, and high water holding capacity make biochar a potential BSM amendment (Inyang et al. 2016, Mohan et al. 2014, Mohanty et al. 2018a, Boehm et al., 2020).

Sand amended with biochar has been shown to improve removal of organics from contaminated waters (Inyang et al. 2012, Macdonald et al. 2015, Inyang et al. 2016, Lu and Chen 2018). Biochar-amended BSM was used to remove trace organic carbon from stormwater runoff in both vegetated and non-vegetated biofilters in two 5-month long stormwater-flushing experiments, during which the removal of organics was more than 99% (Ulrich et al. 2015, Ulrich et al. 2017a). Soil amended with biochar has shown over 50% removal of total and bioavailable PAH compared with soil amended with compost or a compost/biochar mix (Beesley et al. 2010). Because biochar is a relatively homogeneous medium compared with compost or mulch, it is easier to screen based on hydrophobicity to achieve desired specifications. Biochar hydrophobicity can typically be controlled by pyrolysis temperature: a pyrolysis temperature between 500-700°C is optimum to maximize the hydrophobicity of biochar (Manya, 2012, Kinney et al., 2012). Biochar with lower polarity (and higher hydrophobicity) is more effective for removing hydrophobic organic contaminants (Hallin et al. 2017). However, adsorption of these contaminants can be influenced by the presence of other co-contaminants and dissolved organic carbon (DOC). For example, competition for adsorption sites by DOC has been attributed to the detrimental effect of DOC on contaminant removal (Shimabuku et al. 2017).

Biochar has been shown to be effective for removing microbial contaminants from stormwater runoff, although removal can vary by orders of magnitude (Boehm et al., 2020). Biochar demonstrated up to 99.9 % *E. coli* and 90% enterococci removal when added to sand biofilters (Afrooz and Boehm 2017). Performance of biochar-amended biofilters was improved more than two-fold compared to microbial removal in un-amended sand biofilters (Afrooz and Boehm 2017). Biochar not only increased adsorption of *E. coli* from stormwater but also decreased *E. coli* mobilization during intermittent infiltration of stormwater by minimizing the drainage of water from BSM by gravity during inter-event periods (Mohanty et al., 2014b). Vegetated biofilters containing sandy-loam BSM amended with biochar demonstrated over 90% and 95% removal capacity for adenovirus and cryptosporidium, respectively (Chandrasena et al. 2017).

The capacity of biochar to remove heavy metals and nutrients is limited compared to the removal of bacteria and organics. Typically, biochar produced at low pyrolysis temperature is suitable for heavy metal removal (Qian et al., 2016). Biochar with carboxyl and sulfonyl groups are most effective for removing heavy metals (Mohan et al. 2014). Oxidized biochar is more efficient in heavy metal removal than unmodified biochar (Xue et al. 2012). Multiple studies reported higher removal of Pb and Cu by biochar compared to As, Cd, and Zn (Xue et al. 2012). Based on the biochar composition and heavy metal species, biochar-amended BSM can remove between 17-75% of heavy metals in bioretention systems (Reddy et al. 2014b).

The presence of compost in BSM may influence the efficacy of biochar as a BSM amendment. For example, reduced bacterial removal capacity of biochar was observed in the presence of compost within the BSM (Mohanty and Boehm 2014). Adding biochar to a BSM demonstrated no effect on reducing organic carbon, N, or P leaching from the compost-based BSM (Iqbal et al. 2015). In one case, addition of compost increased biodegradation and subsequent release of micropollutants (Ulrich et al. 2017a, Ulrich et al. 2017b).

4.1.2. Peat moss

Peat moss is formed via microbial oxidation of decomposed trees and plants under moist condition and consists of lignin and cellulose (Pouliot et al. 2015). Due to its porous structure and polar functional groups, peat moss is an efficient absorbent for dissolved contaminants including heavy metals and organics (Brown et al. 2000). A non-renewable material, raw, mined peat moss from peatland often needs activation, i.e., thermal or chemical pretreatment, to be used as an effective, structured soil media additive (Brown et al. 2000). Natural peat moss is usually well graded: the particle size varies from 0.2 mm to 4 mm with an average particle size of 0.5 to 2 mm (Abad et al. 2005).

Use of peat moss as a BSM amendment is inspired by its excellent performance in wastewater treatment for removing heavy metals (Brown et al. 2000, Clark and Pitt 2009). This may be attributable to the lower pH reported for peat moss amendments in previous studies (Table 3). Multiple studies have validated the efficacy of filter media amended with peat moss to remove heavy metals (66-91%) from stormwater runoff (Al-Faqih et al. 2008, Bester et al. 2011, Clark and Pitt 2009, Pitt et al. 2004). Peat moss is also reported to remove organic contaminants including biocides (82-100%) and PAHs (up to 95%) from stormwater runoff (Bester et al. 2011, Zhou et al. 2003). However, removal of other stormwater contaminants, including nutrients and microbial contaminants, with the addition of peat moss is minimal (Clark et al. 2002).

4.1.3. Coconut coir

Coconut coir dust or coco coir is a byproduct of industrial processes that recycle coconut fiber to usable products. High internal porosity, heterogeneous surfaces, and high cation exchange capacity makes coco coir a good filter medium and possible amendment to BSM (Noguera et al. 2003). Coconut coir is composed of cellulose, pentosan, furfural, and lignin with carbonyl and hydroxyl functional groups. Except for its infrequent use in tropical areas as a planting media, coconut coir has limited commercial value (Evans et al. 1996). The particle size of coconut coir dust ranges from 0.1 mm to 2 mm with an average particle size of 0.5 to 1 mm (Abad et al. 2005, Evans et al. 1996).

Coconut coir is particularly useful in removal of heavy metals from stormwater. In a laboratory-scale column study using synthetic stormwater runoff, coco coir removed more than 90% of influent Zn and Cd (Lim et al. 2015); however, the removal capacities for other metals were lower: 54% and 74% for Cu and Pb, respectively. Field scale sand biofilters augmented with coconut husks/coconut fibers in the southern Caribbean demonstrated up to 90% removal of nitrate, P, and fecal indicator bacteria from natural stormwater runoff (Tota-Maharaj and Cheddie 2015). While coco coir may perform in a similar fashion to compost in the removal of contaminants such as heavy metals, little or no leaching of P from coco coir makes it a preferable BSM amendment compared to compost (Strecker et al. 2017).

4.1.4. Other organic amendments

Other organic carbon materials such as wood chips, mulch, and granular activated carbon (GAC) have been proposed as BSM amendments to minimize or replace the use of compost (Hunt et al. 2006). In addition, shredded newspaper was reported as an efficient amendment for nitrate removal (>99%) (Kim et al. 2003, Randall and Bradford 2013). However, compared with biochar, these are not as commonly used or cost-effective (in the case of GAC) for stormwater applications (Mohanty et al., 2018).

4.2. Inorganic amendments

While carbon-based amendments provide low-cost options for BSM with good plant support, they biodegrade and require replenishment periodically. In contrast, inorganic amendments are often non-biodegradable and can be readily available via commercial supply chains, sometimes as byproducts of industrial processes. Inorganic amendments can either be coated on sand particles or mixed directly into the BSM. In some cases, the inorganic amendments are used as a polishing treatment layer to prevent or reduce contaminant leaching from conventional BSM. Table 4 lists the most common inorganic amendments implemented for stormwater treatment.

4.2.1. Iron-based Amendments

Iron-based amendments to BSM remove contaminants through the processes of sorption, precipitation, oxidation, and reduction (Cundy et al. 2008). Substantial removal of several heavy metals by BSM with iron-based amendments have been reported in the literature (Rangsivek and Jekel 2005, Reddy et al. 2014). BSM with iron-based amendments are also known to remove P from stormwater via precipitation/adsorption (Erickson et al. 2012, Liu and Davis 2014, Reddy et al. 2014a, Rosenquist et al. 2011); observed removal efficiencies vary from 60-90% for TP. Moreover, sand coated with iron oxide demonstrated up to 4 log removals (99.99%) for *E. coli* removal from synthetic stormwater (Mohanty et al. 2013a). However, the presence of DOC may deteriorate the contaminant removal efficiency of filter media containing iron-based amendments. This is because the net positive surface charge of iron oxide around neutral pH is reversed to net negative surface charge by adsorption of DOC, which consequently increases repulsion between bacterial or viral surfaces and iron oxide (Mohanty et al. 2013a). For example, the effectiveness of iron oxide-coated sand or zero-valent iron for biological contaminant and heavy metal removal decreased significantly (Rangsivek and Jekel 2005) or completely reversed in the presence of DOC (Mohanty et al. 2013b).

4.2.2. Fly Ash

Fly ash, the non-combustible inorganic impurities from coal combustion, is primarily composed of silica, aluminum oxide, iron oxide, and lime. The relative composition of the metal oxides in fly ash varies based on the quality of the pulverized coal fed into the power plant. Fly ash is alkaline in nature and its use with gypsum as soil amendments provides support for healthy plants and increases crop yields in acidic soil (Lee et al. 2003). The internal porosity of fly ash along with its surface characteristics make it an excellent sorbent for P (Zhang et al. 2008a) and heavy metals (Zhang et al. 2008b) removal from stormwater via precipitation and chemi-sorption.

Using a higher percentage of fly ash as a BSM amendment may further increase the contaminant removal capacity the media, though hydraulic conductivity levels would subsequently decrease (Zhang et al. 2008a). BSM amended with fly ash has been linked to improved removal of heavy metals (Liu et al. 2018), soluble reactive phosphorous (SRP) (Li et al. 2018), and was observed to outperformed other amendments, including WTR and zeolite (Jiang et al. 2019).

Table 4
Properties of inorganic BSM amendments reported in the literature.

Amendment	Source material	Specific Surface Area (m^2/gm)	Surface charge	Cation exchange capacity (cmol/kg)	Cost per cubic yard (approx.)	% in BSM	Target Pollutant
Iron filings	Waste iron products	13.73 (Hassapak et al. 2015)	-	-	$12,250[a]	1-5	Bacteria, Phosphorus
Iron-oxide coating	Manufactured absorbent	-	-	-	-	5-10	Bacteria, metals, phosphorus
Fly Ash	Residuals from coal burning	15-20 (Wdowin et al. 2014)	-15 to -25 (Weng and Huang 2004)	0.6-1.8 (Querol et al. 2001)	$35[b,c]	2-5	Metals, Phosphorus
Zeolite	Natural or industrial synthesis	15-90 (Li and Bowman 1997, Tang et al. 2015, Wdowin et al. 2014)	-20 (Kuzniatsova et al. 2007)	9-250 (Li and Bowman 1997, Querol et al. 2002)	$350-$400[d]	10-30	Metals, bacteria
WTR	Residuals from drinking water treatment plant	3-25 (Makris et al. 2005)	-	34.78 (Mahdy et al. 2008)	$0	10-20	Phosphorus

Note: Cost calculations for iron filings and fly ash assume bulk densities of 4860 lb/cy (2283 kg/m^3) and 1620 lb/cy (961 kg/m^3), respectively. References:
[a] Industrial Research, Inc. 2016;
[b] Cemex USA 2020;
[c] The Aberdeen Group 1985;
[d] Hinman and Curtis 2017

4.2.3. Zeolite

Zeolites, which are widely used aluminosilicate sorbents, are natural or synthesized minerals. Due to their porous structure, high specific surface area, and excellent cation exchange capacity, zeolites can remove a wide range of chemical compounds via absorption (Bailey et al., 1999). Zeolites can also be modified by adding salts, surfactants, or antimicrobial agents to develop positively charged surfaces for removing microbial contaminants. In multiple batch tests, both natural and synthetic zeolites removed more than 90% of various heavy metals, including Zn, Cu, Pb, and Cd, in stormwater (Pitcher et al. 2004, Seelsaen et al. 2006, Wu and Zhou 2009). In addition, both natural and surface-modified zeolite were used to remove microbial contaminants from stormwater (Li et al. 2012, Li et al. 2014); zeolite-modified biofilters demonstrated 2 to 3 times higher removal capacity than unmodified biofilters. However, the performance of zeolites modified with metals (e.g., Cu, Zn), metal oxides (e.g., CuO, TiO_2), or antimicrobial compounds (i.e., 3-(trimethoxysilyl) propyldimethyloctadecyl ammonium chloride, $ZnSO_4•7H_2O$) exhibited superior bacterial removal compared to unmodified zeolite (Li et al. 2014). Bioretention columns containing zeolite amended BSM had larger adsorption capacities and operational lifespans for removal of ammonia compared to columns containing various amendments, including WTR and fly ash, as well as non-amended BSM (Jiang et al. 2019). As ion exchange is the primary removal mechanism for ionic pollutant removal in zeolites, the presence of a high quantity of dissolved salts could leach the absorbed contaminants from zeolites.

4.2.4. Water treatment residuals

Residuals from municipal drinking water treatment plants, also termed hydrosolids, are byproducts from the coagulation/flocculation process. Depending on the types of coagulant used, water treatment residuals (WTR) can be iron-, aluminum- or calcium-based amendments to BSM. Due to the high percentage of divalent metal content, WTR are excellent absorbents for removing P from stormwater (Lucas and Greenway 2010, Lee et al. 2015a, Liu and Davis 2014, O'Neill and Davis 2011, Palmer et al. 2013, Zhang et al. 2018). While WTR-amendments may not be efficient in removing N from stormwater runoff, providing an IWS zone in the WTR-amended BSM may provide simultaneous nitrate and orthophosphate removal in bioretention systems (Palmer et al. 2013). Promoting the use of WTR as amendments to BSM offers municipalities an opportunity to both reuse waste materials and reduce disposal costs of WTR that would otherwise be delivered to landfills (Poor et al. 2019).

5. Challenges in developing new BSM specifications

5.1. Retrospective Review Methodology

We analyzed the five most common low-cost and widely available BSM amendments that, based on the review of literature, improve stormwater quality significantly. Data for nutrient and heavy metals adsorption capacity were collected based on peer-reviewed articles that analyzed the capacity of these amendments in adsorbing the target contaminants under varying conditions (e.g. pH, water matrix, temperature). The studies were selected based on keyword combinations "amendment name" and "contaminant name" in the Web of Science database. Only peer-reviewed manuscripts were evaluated, of which selected articles were included if the absorption capacity was reported in the article. Data for biochar, zeolite, fly ash, and coconut coir were gleaned from studies that produced these amendments from different feedstocks through laboratory or industrial processes at different temperature, while data for iron-based amendments involved studies of red mud, iron-based WTRs, and iron fillings. Factors which impart variability into BSM amendment performance were gleaned from this meta-analysis and are discussed below.

5.2. Adsorption capacity of amendments could vary by orders of magnitude

Despite consistently better performance of amendments compared to a sand or soil control (i.e., no amendment), their performance is unpredictable, as contaminant removal capacities can vary by orders of magnitude based on contaminant type, the amendment used, and the conditions in the bioretention systems (LeFevre et al. 2014, Fig. 4). Similarly, removal of dissolved nutrients vary widely between amendment type (Fig. 5). While zeolite is an excellent adsorbent for ammonium (Thornton et al. 2007) and poor adsorbent for phosphate (Berretta et al. 2018), fly ash works well for phosphate removal (Li et al. 2006) and poorly for

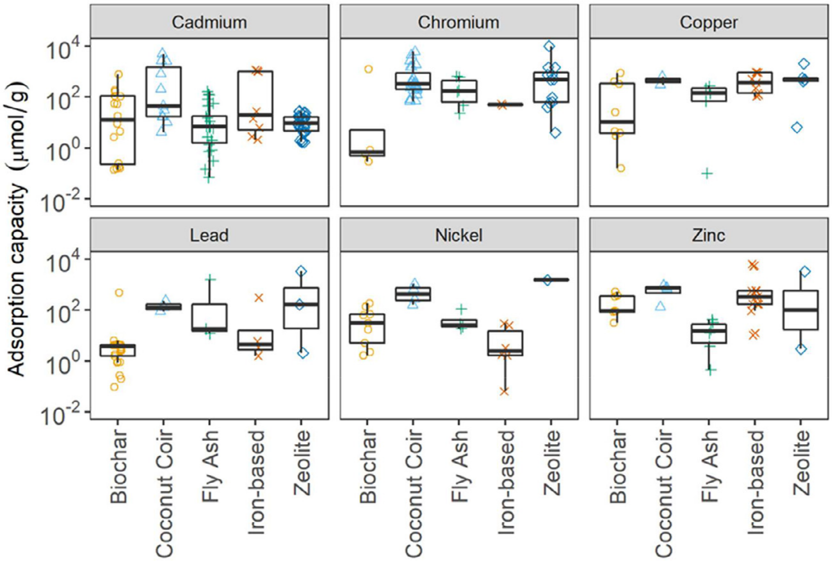

Fig. 4. Comparison between removal capacities of six common alternative BSM amendments for different heavy metals including cadmium, chromium, copper, lead, nickel, and zinc. A total of 62 studies and 301 data points were included in the boxplots. Data and sources provided in the Supporting Material.

ammonium removal (Pathan et al. 2002). Consequently, the BMP designer may use a mixture of amendments based on the nutrients or metals that need to be controlled at a site (Gu et al. 2015). Compared to nutrients and metals, where an amendment may have high capacity to remove specific pollutants, no single amendment exhibits consistently high removal capacity for the removal of bacterial contaminants (Fig. 6). Further, the removal capacity of each amendment could vary widely based on how they are prepared or stored (Suliman et al. 2017), percent of amendment added to the BSM (de Rozari et al. 2015), and type of bacterial pathogen (Abit et al. 2014). For instance, bacterial removal by biochar varies widely due to pyrolysis temperature (Suliman et al. 2017), percentage by weight in the BSM (de Rozari et al. 2015) and pathogen strain (Abit et al. 2014).

5.3. Lack of testing of amendments in field or field relevant conditions

Most laboratory studies measure an amendment's adsorption capacity, the maximum mass of a pollutant that can be removed per unit mass of amendment before they become exhausted. While adsorption capacity is a commonality that can be compared among amendments, it does not necessarily inform the actual removal of contaminants in bioretention systems because the removal could also vary based on hydraulic residence time and competing constituents contained in the stormwater matrix (Rahman et al. 2020). For example, decreased hydraulic retention time or increased infiltration rate of stormwater could severely limit the adsorption of pollutants irrespective of their adsorption capacity (Berger et al. 2019). Similarly, presence of DOC and dissolved salts could decrease adsorption of metals and other contaminants on amendments (Huber et al. 2016, Marsalek 2003, Rangsivek and Jekel 2005). Thus, laboratory experiments should fully include these complexities to quantify a realistic removal capacity of amendments.

Unlike the laboratory, field conditions in bioretention cells are dynamic due to intermittent inundation with stormwater punctuated by periods of drying, freeze-thaw cycles, and variations in stormwater chemical composition. These conditions could increase the aging rate of the amendments and release sequestered pollutants (Costello et al. 2020, Mohanty and Boehm 2015, Rahman et al. 2020). For example, heavy metals in association with soil colloids were released from BSM subjected to dry-wet (Mohanty et al., 2015) or freeze-thaw cycles (Mohanty et al., 2014). Furthermore, amendments in stormwater treatment systems near roadsides or sidewalks may undergo compaction, which could affect bacterial removal capacity by deteriorating the physical integrity of biochar and compost and increasing clogging (Ghavanloughajar et al. 2020, Le et al. 2020). Computational models of amendment performance in field conditions need to incorporate both aging of amendments and clogging of amended BSM.

There are a paucity of field studies which explore the performance of BSM amendments (Ashoori et al. 2019, Kranner et al. 2019, Tian et al. 2019). Further, most laboratory tests neglect control trials (i.e., BSM with no amendments) to benchmark amended BSM performance. Standardized testing procedures are also needed to consistently characterize the properties of BSM amendments to facilitate comparisons between studies to better understand their effects on stormwater treatment performance. Thus, future studies should focus on pilot-scale studies with appropriate controls using standardized testing procedures so that a correlation between removal and corresponding changes in physio-chemical properties of amendments can be deduced.

5.4. Support for plant growth from amendment in field studies is unknown

Amendments like biochar and coconut coir have been shown to improve soil fertility and benefit plant growth (Mohanty et al. 2018, Widyastuti et al. 2020). However, there is a lack of studies of the effect of zeolite, fly ash, and iron-based amendments on plant growth. For instance, fly ash can increase soil pH and release heavy metals (Matsi and Keramidas 1999, Wang et al. 2019), which could diminish plant health (Khan et al. 2015), seed germination (Li et al. 2005) and cause shifts in the soil microbiome (Chen et al. 2018). However, fly ash can also cause release nutrients which could significantly improve plant health (Lee et al. 2006). Moreover, iron-based amendments

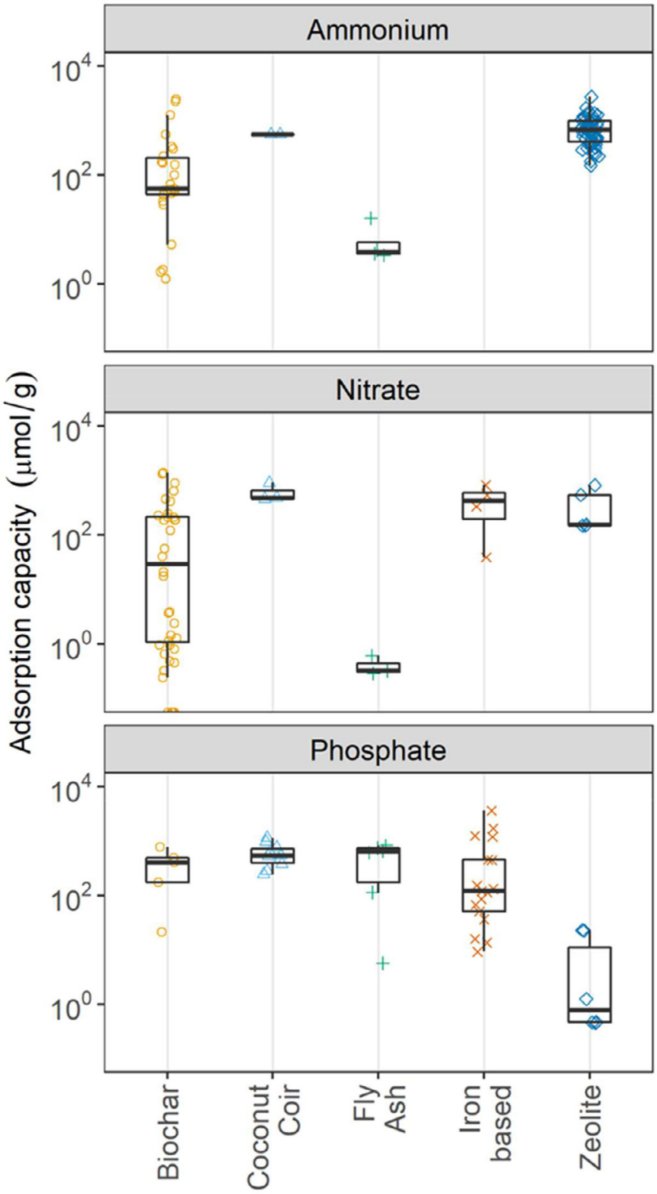

Fig. 5. Comparison between removal capacities of six common alternative BSM amendments for dissolved nutrients including ammonium, nitrate, and phosphate. The boxplot analysis was conducted using 66 studies and 200 data points. Data and sources provided in the Supporting Material.

can improve plant growth and health by providing iron directly as a micronutrient to the plant (Robin et al. 2008) or by retaining organic carbon (Bradley et al. 2011), although such DOC may or may not be bioavailable (Howitt et al. 2008).These studies did not directly investigate stormwater treatment systems, where drying and other natural stressors could simultaneously affect plant health. Therefore, further studies should focus on amendment-plant interaction in field conditions to certify that such amendments have positive ecological effects rather than only removing contaminants.

5.5. *Lack of cost-benefit analysis*

Irrespective of the performance of amendments, their utility in stormwater treatment systems is limited if they are cost prohibitive. In general, waste materials (e.g., WTR) or materials produced from waste biomass (e.g., compost or biochar) are less expensive compared to surface-functionalized amendments (e.g, modified zeolite or iron-filings) (Table 3 and Table 4). Thus, not all novel amendments, even though they may effectively remove contaminants, may be feasible for field applications. The cost of BSM amendments is also affected by shipping costs. If a local source is available for a specific amendment, the cost of applying that amendment for the BSM would be much lower compared to an amendment which needs to be transported or delivered from non-local sources. Therefore, cost-benefit and life-cycle analyses are needed to inform regulatory agencies of the potential benefits that may be realized using these BSM amendments in stormwater management (Allerhand et al. 2012). For instance, as the source material for some of the amendments discussed herein are otherwise considered waste products (e.g., WTRs), municipalities may realize economic benefits associated with reduced disposal costs, which, in conjunction with the potential for improved contaminant removal, may further incentivize their adoption into existing BSM specifications.

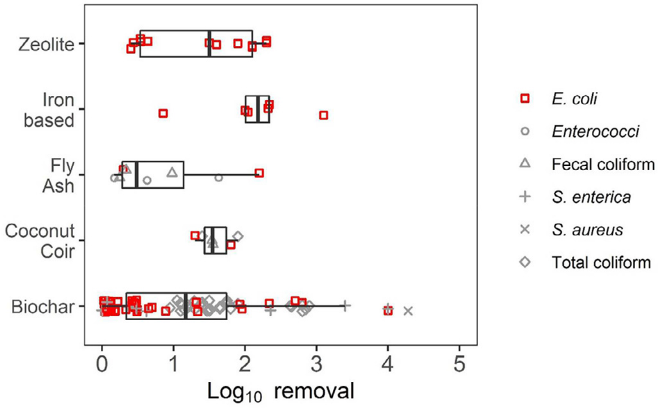

Fig. 6. Comparison between log removal capacities of six common alternative BSM amendments for bacterial pollutants. Data points (n = 147) used to create the boxplots were collected from 17 different studies. Data and sources provided in the Supporting Material.

6. Guidance for Amendment Selection

Though the composition of BSM may be limited by local, state/provincial, or national specifications, use of amendments may be guided by several factors, including the presence of specific, dissolved pollutants of concern, feasibility of amendment costs, and local sources of amendments. Based on the literature reviewed herein, the following decision framework is proposed for selecting BSM amendments (Fig. 7). The use of amendments to BSM should be considered if there is a need to enhance treatment of a particular dissolved pollutant, for instance to meet load allocations set forth in a total maximum daily load for an impaired water body. Amendment selection should be primarily informed by the target pollutant, prioritizing materials which enhance removal performance based on published adsorption capacities synthesized in Figs. 4–6. Following selection, amendment costs should be examined, considering both estimates of amendment cost (Table 3 and Table 4) and proximity to local amendment sources, which could affect delivery and shipping costs. Cost prohibitive amendments should be subsequently replaced by less expensive amendments which still provide improved treatment of target pollutants vis-à-vis traditional BSM (e.g., iron-based amendments should be considered to target pathogen removal if biochar is cost prohibitive for a given BSM). Once an amendment is selected, it can be incorporated into a BSM, considering local design factors (e.g., required BSM hydraulic conductivity), prior to final installation.

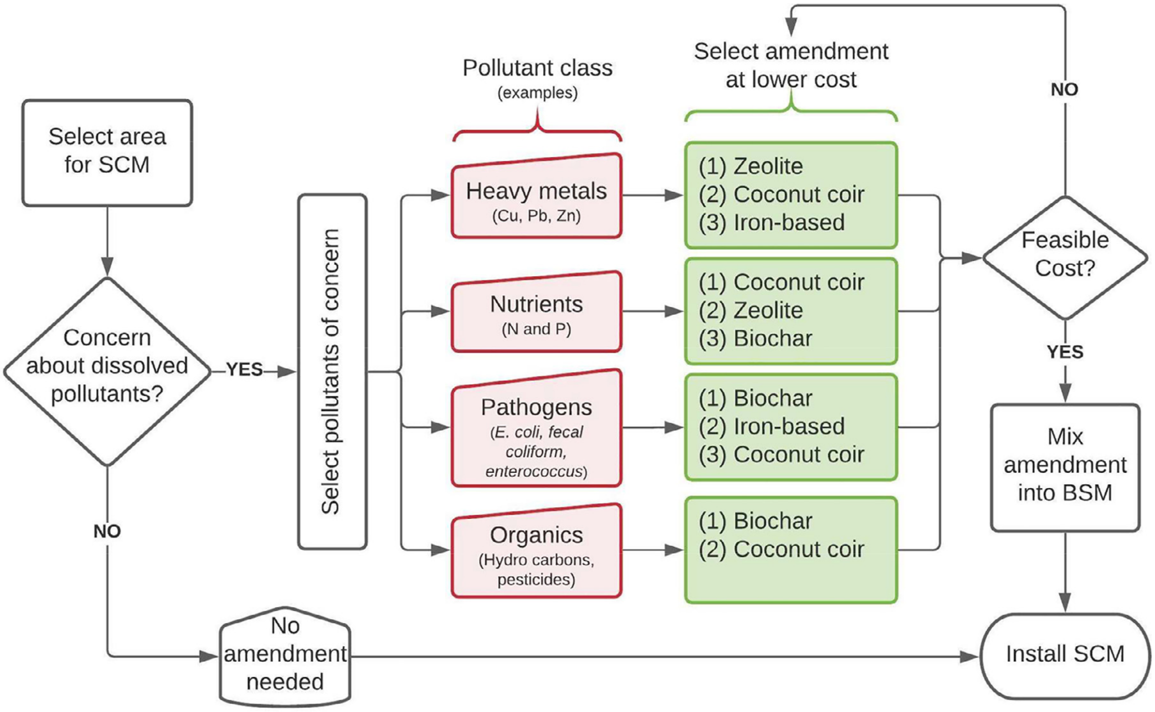

Fig. 7. Flow chart depicting the decision framework from which to select BSM amendments based on pollutant of concern and amendment cost.

7. Conclusions

- Traditionally designed BSM efficiently removes particulates and particulate-bound pollutants but struggles to remove dissolved metals and nutrients from stormwater. Pollutant removal in BSM varies by orders of magnitude depending on the pollutant of interest. This uncertainty in removal makes it challenging to predict field performance.
- BSM specifications vary substantially between jurisdictions. Such specifications are typically loamy sand or sandy loam soil with organic matter (e.g., compost, wood chips, etc.) blended into the mix. The BSM is designed particularly for hydraulics and is not typically optimized for dissolved pollutant removal. Regulatory agencies have been slow to credit and incentivize BSM amendments, and therefore they are infrequently applied at field-scale.
- Many BSM amendments are effective at providing notable improvement in pollutant removal, including biochar, peat moss, coconut coir, iron-based amendments, fly ash, and zeolite. These amendments are available naturally or as waste byproducts and can therefore be relatively inexpensive to implement.
- The performance of various of amendments on pollutant removal is dependent on unit processes and pollutant type. Thus, blending of amendments may be necessary to maximize their capacity to remove a mixture of pollutants.
- Life cycle assessment and cost-benefit analysis must be done to understand the long-term viability of BSM amendments.
- Existing laboratory studies on BSM are difficult to compare, as the experimental conditions vary widely. A control BSM is often missing in many of the studies we reviewed, making it difficult to translate the marginal benefit provided by the BSM amendment. Further, translation of lab scale research to field scale is fraught with potential errors; further studies of BSM amendments at field scale along with standardized testing methods are needed to support widespread use.
- To promote the use of amendments in BSM, regulatory agencies should develop BSM specifications that allow designers and engineers the flexibility to include approved amendments in media mixtures based on their capacity to remove target pollutants.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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