Review of the Emerging Use of Activated Carbon or Biochar Media as Stormwater Source Controls

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Disclaimer

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This project was conducted under the mentorship of Metro Vancouver staff. The opinions and recommendations in this report and any errors are those of the author and do not necessarily reflect the views of Metro Vancouver or the University of British Columbia.

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Glossary

Activation	A term used to describe the use of heat or chemicals for changing the inherent physical and chemical properties of a compound (activated carbon or biochar). Usually, activation is used to increase the surface area of the compound for greater adsorption capacity. Physical activation using hot gases includes carbonization (compound pyrolyzed at high temperatures between 600-900℃, in an inert atmosphere containing argon or nitrogen). Chemical activation involves using impregnation of the compound with chemicals (acid, base, or salt) at a lower temperature (250-900℃).
Bioaccumulation	A term used to describe the gradual accumulation of substances (pollutants) in a media; it occurs when the rate of adsorption on the media surface is greater than the amount of degradation of the pollutant. The growth of microbial ecosystems in/on the media can help reduce bioaccumulation.
Biofiltration	A pollution control technique that uses microbial activity for capture and biological degradation of pollutants.
Bioretention	Particularly for stormwater runoff treatment, it is a process to remove pollutants and sediments. Runoff is collected in a treatment system, where it first flows through a sand bed (to slow down the runoff velocity). Then, the filtered runoff is distributed over another organic later or groundcover and underlying planting soil.
Best management practices (BMPs)	A term commonly used in America to describe a principal control or treatment technique and includes structural or engineered control devices or systems to treat polluted stormwater as well as operational or procedural practices.
Carbon sequestration	A term used to describe the long-term capture of carbon dioxide form the atmosphere and helps mitigate atmospheric CO2 pollution to mitigate or reverse global warming.
Contaminants of emerging concern (CECs)	A term used to describe pollutants that may cause ecological or human health impacts and are currently not regulated under environmental laws. The emerging concern is due to the fact that the risk of these pollutants on human life is not fully understood or known. Some emerging contaminants can cause endocrine-disrupting activities and other toxic mechanisms. To be classified as a CEC, two main requirements are to be met: - Human life has been hampered by the effects of the compound in any part of the world - There is an established relationship between the positive and negative effects of the compound

Exhaustion	A term used to describe that the adsorbent media is completely saturated by the adsorbate. Regeneration or replacement of the media may be needed after exhaustion.
Leaching	A term used to describe the loss or extraction of certain compounds (water-soluble) from the media into a liquid
Low-impact development (LID)	A term commonly used to describe land planning and engineering design approaches to manage stormwater with green infrastructure. Conservation and use of on-site natural features are utilized to protect water quality.
Sorption	A term used to describe the physical and chemical processes by which one substance attached to another. There are three types of sorption: absorption, adsorption, and ion exchange
Pyrolysis	A term used to describe the thermal decomposition of materials (usually organic) at elevated temperatures in an inert atmosphere.
Source control	A term used to describe the different measures that can be taken to manage stormwater close to where it falls, in the form of treatment or volume capture.

Contents

Executive Summary

Stormwater runoff in an urban area is a complex mixture of pollutants originating from rooftops, pavement wear, tire wear, spills and leaks, soil litter, organics from birds or animal wastes, and other chemicals. Most of these pollutants can be grouped into four main categories of pollutants viz., suspended solids, metals, organics, and contaminants of emerging concern (CECs). Filtration and infiltration media based stormwater treatment systems, with plants grown over the media, have traditionally been used for the removal of solids, metals, and organics. However, the viability of such systems for the removal of emerging contaminants is a concern. Engineered media using black carbons - activated carbon (AC) and biochar, have a lot of potential in removing many of the pollutants.

The project entitled "*Review of the Emerging Use of Activated Carbon or Biochar Media as Stormwater Source Controls*" explores the use of these engineered media for stormwater management. The project's scope included research, in the form of literature review and interviews with relevant stakeholders, and has been presented in this report through three main sections: *Theory*, *Application*, and *Conclusion*.

The *Theory* section includes present research into pollutant removal performances of activated carbon (AC) and biochar. The main pollutants that have been explored are metals, CECs, and nutrients. Activated carbon, in granular, powdered or pelletized form, can be produced from a variety of materials like agricultural wastes and temperature-dependent production methods. Heavy metals like Pb, Zn, Cu, Cd, Ni, and Hg can be removed by ACs, with variable removal efficiencies reported in literature. CECs like atrazine, PAHs, and some hydrophobic organic compounds can be removed by AC as well, but there are some concerns with bioaccumulation of the CECs in the AC media and their uptake by plants. Biochar, with similar production methods as AC, can be obtained from organic biomass and agricultural waste materials. Biochar can also remove similar heavy metals as AC, with lower reported removal efficiencies. Biochar has shown considerable promise for the removal of various chemicals like RDX and TNT, pharmaceuticals, pesticides, and some trace organic compounds. Some nutrient (ammonia, nitrate, etc) removal has also been observed by biochar media, although removal efficiencies are dependent on biochar blend characteristics and type of plant over the media layer. The removal mechanisms by both AC and biochar are infiltration and filtration based, however it depends greatly on the physical and chemical properties of the raw material used for media, production method (temperature), and type of sand/soil and plants in the stormwater treatment systems.

The *Application* section includes case studies on-field or pilot-scale application of activated carbon and biochar for stormwater management. It was evident that the current application of the AC and biochar media for stormwater management falls into themes of stormwater runoff volume reduction opportunities, removal of metals, nutrients, and CECs, comparing different media blends for pollutant removal, and soil amendment. Notably, there was no consistency in the type of AC and biochar media (whether designer or commercial) used in field applications, resulting in variable pollutant removal performances. However, contaminant uptake by plants grown on the engineered media and overall soil properties were benefited by the use of AC and biochar media. Engineered media also helped in considerable stormwater runoff reduction, which can be quite useful in an extreme storm event.

The *Conclusion* section summarizes the report into a summary of the main findings from the literature review, some research gaps identified in current research, and finally a few recommendations. Both AC and biochar can remove significant proportions of heavy metals, nutrients, and CECs from stormwater runoff. There are also economic and environmental benefits expected from the use of AC and biochar media. Modification of raw materials, production methods, and implementation in the stormwater treatment systems allow for the development of a variety of ‘designer’ media blends that can be designed for target contaminants and volumetric reduction of stormwater runoff in a particular site. However, the inconsistency of blends as seen in literature pose a significant research gap in the use of these media for stormwater management. There is little knowledge on the fate of the contaminants accumulated in the media, probable leaching of contaminants, and the benefits of plants grown over the media for increased contaminant removal, as most studies are lab-based or have been operating only for a shorter period of time (6 months to a couple of years). Most studies included in literature are also lab-based and the results of which cannot be extrapolated to on-field performances where complex environmental conditions exist.

Overall, there is a significant amount of valuable research currently available on the application of activated carbon or biochar in stormwater management. However, there are as many unknowns as well. A collaborative effort between academia, industry, and policymakers will aid in streamlining all of this research and present a clearer idea on the value of these media. Such collaboration can inform guidelines and regulations surrounding stormwater management resulting in lowered environmental impacts and improved resiliency of urban communities.

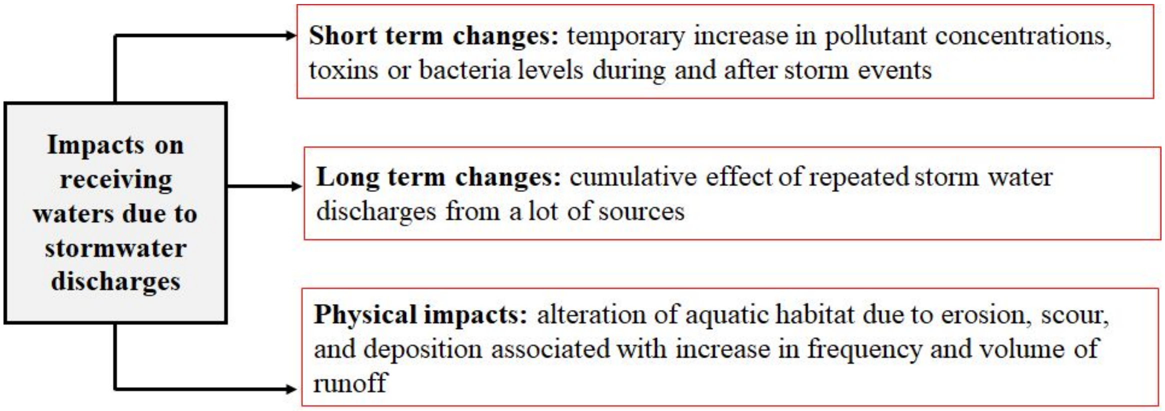
THEORY

URBAN STORMWATER

Urban stormwater may contain wastes and pollutants like nutrients, suspended solids, pathogens, metals and synthetic organics that impact public health and the quality of the environment. Impact of stormwater discharges on receiving waters is a known environmental problem (Gromaire-Mertz, 1998; Rossi, 1998; Burton and Pitt, 2002). This can be particularly damaging for small rivers that accept these discharges (Rossi et al., 2005). Climate change, urbanization development, and other environmental factors (natural disasters like landslides) can impact stormwater pollution (Borris et al., 2016). However, pollutant load prediction is one of the greatest challenges in urban stormwater management.

Pollutants in stormwater

Stormwater can contain up to 650 organic substances, 30 metals, and other trace organic substances (Eriksson et al. 2007). The concentration and load of any pollutant can vary between different rainfall events (precipitation event characteristics and antecedent dry period) or even within a single event (the highest concentration of the largest amount of pollutants occur during the initial period or volume of the stormwater event (first flush/foul flush) (Hvitved-Jacobsen et al., 2010). The adverse impacts of any pollutant depends on properties like persistence, toxicity, and bioaccumulation (Sharma et al., 2016). The performance of the treatment systems for the pollutants can be affected by the characteristics of intermittent stormwater events like rainfall intensity, duration, and antecedent drying period (Li et al., 2012). The US EPA (1995b) classifies impacts on receiving waters due to storm water discharges into three main classes as shown in the figure below:



Impacts on receiving waters due to stormwater discharges

Short term changes: temporary increase in pollutant concentrations, toxins or bacteria levels during and after storm events

Long term changes: cumulative effect of repeated storm water discharges from a lot of sources

Physical impacts: alteration of aquatic habitat due to erosion, scour, and deposition associated with increase in frequency and volume of runoff

Adverse impacts on receiving waters associated with storm water discharges. Modified from EPA (1995b).

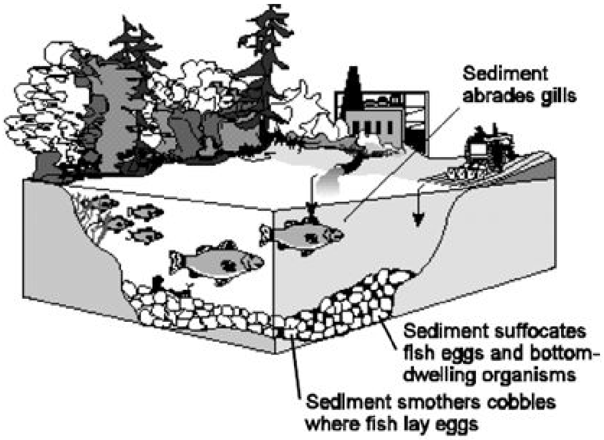
In a comprehensive study on urban stormwater runoff done by the US EPA between 1978 and 1983 - the Nationwide Urban Runoff Program (NURP) for about 2300 stormwater events, the main constituents of urban stormwater were identified as total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total phosphorus (TP), soluble phosphorus (SP), total kjeldahl nitrogen (TKN), nitrate and nitrite (N), total copper (Cu), total lead (Pb), and total zinc (Zn). Median event mean concentrations for these pollutants due to various urban land use are shown in table below:

Median event mean concentration of stormwater pollutants. From US EPA (1983).

Pollutant	Units	Residential		Mixed		Commercial		Open/ Non-Urban	
		Median	COV	Median	COV	Median	COV	Median	COV
BOD	mg/l	10	0.41	7.8	0.52	9.3	0.31	--	--
COD	mg/l	73	0.55	65	0.58	57	0.39	40	0.78
TSS	mg/l	101	0.96	67	1.14	69	0.85	70	2.92
Total Lead	µg/l	144	0.75	114	1.35	104	0.68	30	1.52
Total Copper	µg/l	33	0.99	27	1.32	29	0.81	--	--
Total Zinc	µg/l	135	0.84	154	0.78	226	1.07	195	0.66
Total Kjeldahl Nitrogen	µg/l	1900	0.73	1288	0.50	1179	0.43	965	1.00
Nitrate + Nitrite	µg/l	736	0.83	558	0.67	572	0.48	543	0.91
Total Phosphorus	µg/l	383	0.69	263	0.75	201	0.67	121	1.66
Soluble Phosphorus	µg/l	143	0.46	56	0.75	80	0.71	26	2.11

- **Total suspended solids (TSS)**

TSS can be a major pollutant in stormwater and have deleterious impact on receiving water bodies. Solids can originate from erosion of pervious surfaces, dust, litter, and other particles deposited on impervious surfaces due to human activities.



Possible impact of solids deposition in receiving water bodies (rivers). From US EPA (1998d)

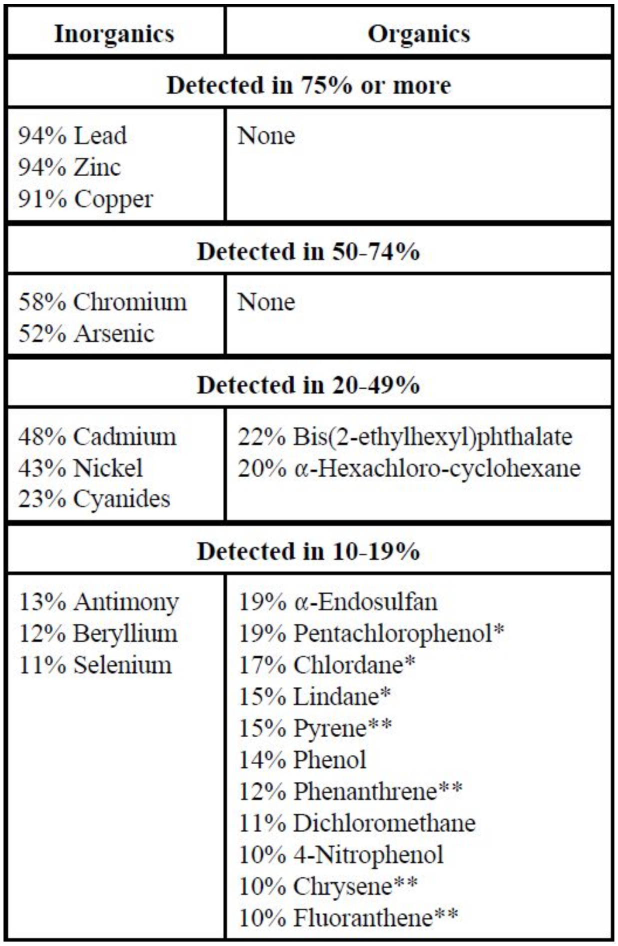
TSS can impact water bodies by increasing water turbidity, inhibiting plant growth and diversity and hence, affecting river biota, and reducing the number of aquatic species (Shamma et al., 2002). Nutrients and toxic metals, metalloids and synthetic organics can readily accumulate, and be transported and stored in TSS (Rossi et al., 2005). Accumulated sediments in receiving rivers can result in biological activity by pollutant desorption, transformation or particle uptake by organism ingestion and contaminated sediments can have chronic impacts on benthic organisms (Harremoës, 1982; Burton and Pitt, 2002; Rossi et al., 2003).

Typical TSS concentration in untreated stormwater runoff from recycling facilities can range between 100 mg/L to 1000 mg/L (Recycling today, 2014). The US EPA reports the typical concentration of TSS in urban runoff to be about 150 mg/L, as compared to about 20 mg/L in domestic wastewater after secondary treatment (Bastian, 1997).

- **Metals**

The presence of heavy metals in stormwater is quite commonly studied. A substantial amount of metals are deposited and mobilized due to transportation activities (vehicle exhaust, brake linings etc), construction (soil erosion, exposed metal etc), and other industrial activities (power plants, cement kilns etc). Due to storm events, these metals can be transported in dissolved, colloidal, and suspended solid forms via stormwater to the soil or receiving waters. In highly developed areas, higher concentrations of cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), and zinc (Zn) are commonly found in stormwater. Zn, Cu, and Pb are some of the most prevalent metals found in stormwater runoff in urban areas (US EPA, 1983). Sansalone and Glenn (2000) found that Zn and Cu are primarily found in dissolved form, and Pb is usually bound to a particle or dissolved.

Heavy metal detection in Nationwide Urban Runoff Program (NURP) study From US EPA (1983)



Inorganics	Organics
Detected in 75% or more	
94% Lead 94% Zinc 91% Copper	None
Detected in 50-74%	
58% Chromium 52% Arsenic	None
Detected in 20-49%	
48% Cadmium 43% Nickel 23% Cyanides	22% Bis(2-ethylhexyl)phthalate 20% α-Hexachloro-cyclohexane
Detected in 10-19%	
13% Antimony 12% Beryllium 11% Selenium	19% α-Endosulfan 19% Pentachlorophenol* 17% Chlordane* 15% Lindane* 15% Pyrene** 14% Phenol 12% Phenanthrene** 11% Dichloromethane 10% 4-Nitrophenol 10% Chrysene** 10% Fluoranthene**

Heavy metals in receiving waters can be toxic to aquatic organisms, and are recognized as “priority pollutants”. According to Ma et al (2016), the toxicity of metals is higher when they bioaccumulate, and the risk order is:

$$Pb > Cd > Cu > Zn.$$

Concentrations of heavy metals in stormwater can be highly variable, and are dependent on the type of surface where precipitation occurs, the degree of contamination of the catchment area, and characteristics of precipitation (Sakson et al., 2018). Metals concentration in stormwater is usually reported in mg/L or µg/l (Recycling today, 2014). In a study carried out at Lodz, Poland, the content of heavy metals in an urban catchment discharge were studied. It was observed that Zn concentrations were variable in traffic area runoffs due to its presence in galvanized structures and crumbs of car tire rubber, low in residential areas, and highest in industrialized areas. It was often observed that the concentration of metals in stormwater far exceeded the permissible limits for industrial wastewater into receiving waters and limits for surface water of good quality. In another study done in Curitiba, Brazil (Prestes et al., 2006), Pb and Cu concentrations in drainage water (from 21 storm events) were found to be in the ranges of 15 and 8.3 µg L^{-1}, respectively; with the highest concentrations reported due to deterioration of vehicle brakes and tires, runoff from roofs, and dry deposition.

In a study done by Tuccillo (2001) on the presence of heavy metals in stormwater, preliminary results revealed Cu and Zn in the stormwater from all outfalls. Cu concentrations ranged from 3.4-50.0 ug/L and Zn concentrations ranged from 17.4-135.0 ug/L. Both metals were predominantly in the dissolved phase. Cd was not detected in any sample. Trace amounts of Cr and Ni were detected in one sample, and trace amounts of Pb were detected in two samples; these values were extremely close to the method detection limits.

- **Nutrients**

Nitrogen and phosphorus are pollutants of concern in urban stormwater. The main sources are urban landscape runoff (fertilizers, detergents, plant debris), atmospheric deposition, inefficient septic systems, and animal waste (Terrene Institute, 1996).

Excess nutrients in water bodies can accelerate primary biological productivity, resulting in excessive algal growth that leads to nuisance algal blooms and eutrophication. Decomposing algae can deplete dissolved oxygen concentrations at the bottom of the water bodies.

Nutrient content in stormwater is usually measured in terms of ammonia (form of nitrogen readily available to aquatic life), nitrate and nitrite (inorganic forms of nitrogen), total kjeldahl nitrogen (organic and ammonia forms of nitrogen), total phosphorus (organic and inorganic forms of phosphorus), and orthophosphorus (bioavailable phosphorus). Nutrient levels in stormwater are significantly less than wastewater, however, may increase during large storm events. Typical watersheds can result in 5 to 20 times as much phosphorus per unit per year as compared to undeveloped watersheds in a given region (Walker, 1987).

- **Contaminants of Emerging Concern (CECs)**

CECs include hormones, urban/agricultural/mixed-use pesticides, industrial compounds, human/veterinary pharmaceuticals, personal care product ingredients, “lifestyle” compounds (e.g., caffeine, nicotine, and cotinine reflect lifestyle more than personal care), and many other commercial-consumer product-related compounds (e.g., benzotriazoles, flame retardants, plasticizers). CECs are usually reported in ng/L.

In a study in Minneapolis-St.Paul, Minnesota, USA, 36 samples from stormwater conveyances (pipes) and iron-enhanced sand filters (IESFs) reported about 123 compounds including commercial consumer compounds, veterinary and human pharmaceuticals, lifestyle and personal care products, pesticides and others (Fairbairn et al., 2018). The most frequently detected CEC in this study was caffeine and triphenyl phosphate (used as plasticizer and fire retardant). Variations in the types of CECs were also observed seasonally; tributyl phosphate (a widely-used flame retardant and solvent in plastics, dyes, and adhesives), lifestyle, pharmaceutical, and commercial-consumer CECs were found in higher concentrations in spring and early summer. The presence of these CECs may indicate combined runoff and wastewater sources to stormwater as most of these compounds (e.g., nicotine, caffeine, lidocaine, menthol) are generally used or disposed of indoors and outdoors. Litter (cigarettes, packaging) contributes nicotine, menthol, and triethyl citrate to runoff and receiving waters (Green et al., 2014). Pharmaceuticals associated with veterinary and human applications like Benzotriazoles (present in windshield washer fluid, anti-corrosives, antifreeze, and aircraft deicers) and PAHs (present in e.g., automotive exhaust, coal tar, tires) which are common in urban environments due to vehicle usage, seal coats, and fossil fuel combustion; leaching or surface deposition with subsequent downgradient transport via stormwater runoff were also detected (LeFevre et al., 2011; Parajulee et al., 2017).

In a study done by US EPA, PAHs accounted for 19% of total detections. PAHs can be extremely toxic for aquatic organisms (oysters) at concentrations above 5000 ng/L and about 42% of locations in the study recorded concentrations of around 10,000 ng/L.

- **Other pollutants**

Some other common pollutants in urban stormwater is discussed in the table below:

Characterization of pollutants in stormwater. Modified from Barbosa et al., 2012, Hvitved-Jacobsen and Yousef, 1991; Wanielista and Yousef, 1993; Burton and Pitt, 2002; Björklund, 2011; Eriksson et al., 2005; Lau and Stenstrom, 2005; McCarthy et al., 2008; Hvitved-Jacobsen et al., 2010.

Pollutant	Sources	Impacts in receiving waters
Biodegradable organic matter (BOD5 and COD)	Vegetation (leaves and logs) and animals such as dogs, cats and birds (either fecal contributions or dead bodies).	No substantial impact but, impacts of dissolved oxygen (DO) balance due to nutrient enrichment, and eutrophication may be significant.
Pathogens (Total coliforms, E.coli)	Main sources are fecal matter from domestic animals - cats and dogs, birds etc; failing septic tanks, illicit sewage connections, and boats and marinas. Coliform counts in stormwater runoff of warmer seasons may be 20 times higher than colder seasons.	Can present a potential public health threat if in contact with receiving waters that are used as a drinking source.

Traditionally, it has been thought that heavy metals and nutrients can be easily removed by organic materials like mulch or plants in the stormwater management systems. However, as newer pollutants continue to appear in stormwater runoff, these traditional systems have not performed well in removal of the pollutants. Hence, new engineered media like activated carbon and biochar has evolved as possible amendments to the filtration media layers of traditional stormwater management systems.

URBAN STORMWATER MANAGEMENT

Urbanization causes many land-use modifications like reduced vegetation, replacement of pervious areas with impervious surfaces which may lead to increased stormwater runoff volumes and peak flows (Barbosa et al., 2012). Sustainable and integrated stormwater management takes into account a variety of factors like water quality, and erosion and flood control (Barbosa et al., 2012). Urban stormwater management is relatively new as compared to sanitary wastewater management.

Drivers for best management practices

Factors that impact stormwater management can be geophysical, social, technical and financial in nature.

Geophysical factors include climate, hydrology, land, soils, and topography (Barbosa et al., 2012). Geophysical constraints are denominated by land like the use, drainage area, and space available for implementing stormwater management solutions. Land use, particularly urbanization, can lead to decreased pervious areas and poor water quality due to pollutants. Drainage area impacts stormwater quality and quantity (Goonetilleke et al. (2005)). Pollutant concentration can be correlated to the watershed area (Lee and Bang (2000)). As most stormwater solutions are physical in nature, space considerations are very important for implementation. Soil type and thickness can influence runoff volumes and pollutant removal (Barbosa and Hvitved-Jacobsen, 2001).

Engineering stormwater solutions are dependent on legislation as well (Hvitved-Jacobsen et al., 2010). The Clean Water Act (1972) in the USA and the Water Framework Directive (2000) in Europe were borne out of a newer approach to water management by incorporating risk management, public information and consultation through georeferenced technology, and establishment and maintenance of monitoring, forecasting, and early warning systems (Barbosa et al., 2012). Such inclusive legislation can help strengthen the public perception of stormwater management challenges and allow for the contribution of the society towards changing paradigms of institutions and politicians as well (Barbosa et al., 2012). Integration of the social factors attuned to spatial planning, urban renewal, traffic, recreation, education, culture, maintenance and management of public areas are very important in stormwater management. Climate change has also become a major factor while considering stormwater management solutions (Barbosa et al., 2012).

Costs related to the proposed stormwater management solutions is a factor considered during the decision making process (Barbosa et al., 2012). Land acquisition, construction, operation, maintenance, and monitoring costs, and other expenses related to the effective duration of the facility and technical training of staff must also be considered (FHWA (2000)). Some of the marketing tools commonly used to encourage end-users and industries to implement stormwater management practices at site and local levels include: price instruments (stormwater fees and charges), allowance markets, and voluntary offset (incentive) programs like stormwater retrofit programs (Barbosa et al., 2012). However, the selection of an appropriate market based approach depends most importantly on the unique physical characteristics of the catchment, legal structure, and social and economic aspects of the community in consideration (Parikh et al., 2005). Total maximum daily load (TMDL) is an approach currently used by the USEPA (as per Clean Water Act section 303 (d)) wherein the maximum amount of a pollutant allowed in a waterbody is established and this serves as the starting point or planning tool for restoring water quality.

The decision behind the most appropriate stormwater management solution is hence dependent on the evaluation of local, regional, and national practices and technical considerations. A simple solution may be adopted if there is an evident lack of technology or methodology in the community, and the design and planning may incorporate possible upgrades in the future. A common approach for decision making in assisting water utilities is Infrastructure Asset Management (IAM) which balances performance, cost, and risk in the long term (Alegre et al. (2011)).

Stormwater management in the Pacific Northwest (PNW)

Field surveys have identified that only a fraction of built environments with watersheds in the Pacific Northwest (PNW) have structural best management practices (BMPs) for stormwater management. It is speculated that the cause of such discrepancy is pre-BMP development, changes in BMP design standards, and lack of uniform regulations across local municipalities (May and Horner, 2002). Low impact developments (LIDs) have been significantly successful in reducing impacts and protecting aquatic ecosystems with added benefits of cost effectiveness. LIDs have been identified as sustainable stormwater management solutions for use in the PNW region due to their service of better on-site runoff and pollutant reduction. LIDs help maintain pre-development hydrological regimes and protect ecological integrity within a watershed. Integrated stormwater management (ISWM) within the development process of the built environment is important; and should not be treated as a mitigation process. ISWM must consider objectives of water quality treatment, and water quantity control (peak, volume, and duration) amongst others. Structural BMPs mimicking natural hydrology of watersheds by innovative technologies like infiltration, bioretention, bioinfiltration are most effective in stormwater management.

Within the province of British Columbia, Canada, ISWM plans are adopted for rainwater management for a range of rainfall events. The responsibility of stormwater management lies on the municipalities. Innovative design elements like absorbent landscapes, green roofs, rain gardens, etc are encouraged. Regulatory guidelines for stormwater in BC include the Fisheries Act, the BC Hazardous Waste Regulation, Schedule 1.2 – "Standard for discharges to the Environment" or to Storm Sewers, the BC Contaminated Sites Regulations, Schedule 6 – "Generic Numerical Water Standards", CCME Water Quality Guidelines for the Protection of Aquatic Life, BC Approved Water Quality Guidelines, and Metro Vancouver's Municipal Water Use Guidelines.

In 2019, the City of Vancouver introduced the Rain City Strategy incorporating green rainwater infrastructure (GRI) and urban rainwater management initiative, with goals of capturing and cleaning 90% (minimum) of Vancouver's average annual rainfall and the first 48 mm of rainfall per day. The design standard is applied at the project, site or district scale whenever rainwater management objectives are included as part of a project scope. The amended design standard will apply immediately to streets and public spaces, parks and civic facilities and will be adopted for private sites by 2022. In addition, the strategy establishes an implementation target for capturing and cleaning rainwater from 40% of Vancouver's impervious areas by 2050. It is estimated that 30% of this total would be achieved by including rainwater management, where feasible, as a standard practice in new capital projects in the public realm and through regulation for new developments in the private realm. The remaining 10% of the total would be achieved through targeted retrofits in the public and private realm.

STORMWATER SOURCE CONTROL

Source control is a cost-effective stormwater management solution that can reduce excessive runoff and pollutant loads entering the drainage system (Barbosa et al., 2012). Environmental impacts from stormwater runoff have been found to be sufficiently reduced by implementing appropriate source control measures (Hvitved-Jacobsen et al., 2010). Source control measures can be non structural like alternative layouts of roads and buildings, minimizing imperviousness and maximizing soil use and vegetation, contaminant reduction and educational programmes to reduce stormwater pollution (FHWA (2000)). Structural measures can be in the form of construction near the stormwater sources like infiltration or rainwater reuse facilities or green roofs (Schroll et al., 2011). A very common source control measure is street sweeping to remove pollutants from streets before being washed out by rain events, however their implementation at a large scale is difficult (German et al., 2005).

Stormwater source control measures with their methodology. Compiled from Hydro International (2020), Trimedia (2015), and Water & Wastes Digest (2002).

Treatment mechanism	**Methodology**	**Advantages**	**Disadvantages**
Screenings	● Physical barriers to screen pollutants in stormwater to prevent them from entering the drainage network.	● Effective against larger pollutants like trash, litter, gross solids and other larger particles. ● Can be combined with a settling chamber to let grit and coarse sediments to settle.	● Cannot screen smaller sized particles.
Separation	● Usually an underground structure wherein hydrodynamic separators use a vortex to separate or retain solids from surface runoff by mechanisms of sedimentation and flotation.	● Cost-effective and can remove oils, hydrocarbons, suspended solids as well as heavy metals, chemicals or nutrients that may be bound to the solids. ● The standalone structure is suitable for paved areas where there is less available space.	● Maintenance of the separators may be required. ● Proprietary flow controls may need to be monitored.
Filtration	● Filtration media or membranes capture the pollutants in the stormwater as it flows through them. ● Most common type of filter media is sand. ● System can be designed as a concrete structure or a small detention area.	● Contaminant selectivity can be obtained to address specific pollutants. Eg: ● Systems near industrial areas can be customized to capture metals (Zn, Cu, Pb, Al). ● Sand filters are best applicable in paved areas (parking lots, garages, driveways) in urban settings with lots of impervious surfaces and drier climates. ● They can also protect groundwater quality.	● Cannot be used for removing larger debris, silt, solids etc. and hence, often must be used in combination with a screen or sedimentation basin. ● Clogging of sand filters and membrane fouling could be an issue.

Infiltration (Low impact development, LID)	● Designed as an underground recharge device, and provide a permeable surface for the stormwater to soak through, mimicking the natural effect of soil. Soil is usually the filter medium.	● Native soils can be engineered with different materials (geomedia like zero-valent iron or iron oxide coated sand, activated carbon, biochar etc) to remove specific pollutants. ● Plants can also be incorporated on site for capturing nutrients and aesthetic purposes.	● Feasibility depends on the sites' native soils. ● Soil property and site geology, slopes, and hydrology impacts performance. ● Clogging may also be an issue. ● Geomedia like iron oxide coated sand can exhaust in the presence of DOC, thereby reducing their removal capacity.
Retention	● Artificial lakes or ponds collect rainwater, and emulate natural water treatment capabilities of watersheds. Particles can settle down by sedimentation, and plants, algae and bacteria in the watershed can remove organic contaminants or nutrients.	● Stormwater storage allows for stormwater treatment and reduces flood risk. ● Plants (grass, shrubs, wetland flora) can capture nutrients while being aesthetically pleasing. ● Wildlife habitat can also be encouraged. ● Can typically function for about 20 years with maintenance.	● Operations are impacted by site hydrology. ● Constructed basins (wetlands) must be able to withstand drought. ● Some pre-treatment may also be needed to prevent sediments from choking the vegetation. ● Upfront costs are quite high.
Dry detention basins	● Commonly known as dry ponds that can confine stormwater only for short periods of time (about 24 hours). During and immediately after storm events, runoff remains in the basin and pollutants can settle at the bottom.	● Provide opportunities for flood control in addition to managing stormwater runoff. ● Applicable to any climate.	● Space limitations can greatly impact the effectiveness (minimum 10 acres are needed (EPA)). ● Must be used in combination with other systems for highly contaminated sites.
Coverings, street sweeping, and nutrient management programs	● Source control measures to prevent or reduce the amount or type of pollutant that can contaminate stormwater. Coverings may be temporary (plastic covering/tarpaulin) or permanent (roof/building /enclosure).	● Coverings are particularly useful in spaces containing raw material, by-products etc. and are easy to implement and cost effective.	● Frequent inspections are required in case of coverings.

Low-impact development (LID) structural source control measures are particularly favoured for stormwater management. Infiltration based LID systems include rain gardens, retention systems, infiltration trenches, bioinfiltration systems (NRC, 2009; Hunt et al., 2010). Structures with porous surfaces can promote the rapid infiltration of rainwater into groundwater or temporary storage (retention basins) and decrease surface runoff. The additional benefit of stormwater treatment also makes LID measures attractive. However, traditional infiltration based stormwater management systems are designed mostly to reduce or delay stormwater flows rather than treatment. Concerns on effectiveness and cost are key considerations in their implementation.

Common Low Impact Development (LID) Systems in urban areas

Most common LID systems in urban areas are:

- **Downspout disconnections**

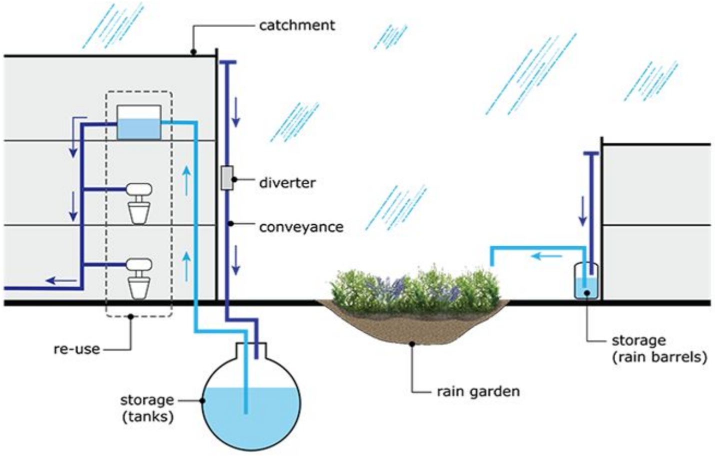
A downspout disconnection is an LID that performs the function of redirecting rainwater from the rooftops into the storm sewer by draining through rain barrels, cisterns, or permeable areas. A properly disconnected downspout allows the stormwater to flow away from the foundation onto the landscaped areas, offering opportunities for stormwater to follow a natural flow into the soil. Overarching benefits of improved water quality in local streams and rivers, water source for personal lawns and gardens, and reduced stress on the sewer networks by redirecting water to the soil.

A disconnected downspout (Campos et al., 2015)

- **Rainwater harvesting systems**

A typical rainwater harvesting system performs the function of collecting and storing rainfall for further usage. Besides collection, these systems can also slow and reduce the overall stormwater runoff and provide a viable source of water.

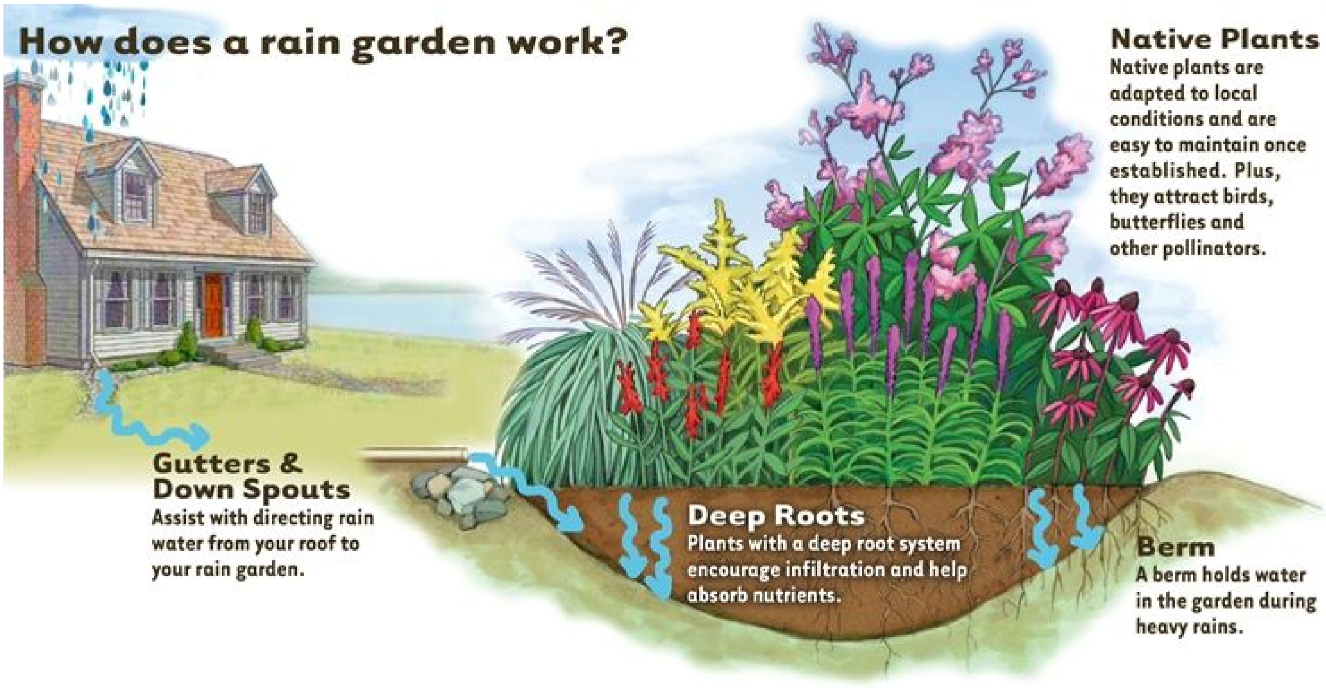
Rainwater harvesting systems can include catchments, coarse meshes, gutter, conduits, filters, storage tanks, and recharge structures.



A rainwater harvesting system (NEXT, 2020)

- **Rain Gardens**

Rain gardens are typical LIDs that can perform the function of filtering and absorbing stormwater runoff from surrounding urban areas. They are also called bioretention or bioinfiltration systems due to the biological processes used to remove contaminants from the runoff. These systems can mimic natural hydrology through infiltration, evaporation, and transpiration.



Native plants are adapted to local conditions and are easy to maintain once established. Plus, they attract birds, butterflies and other pollinators.

Assist with directing rain water from your roof to your rain garden.

Plants with a deep root system encourage infiltration and help absorb nutrients.

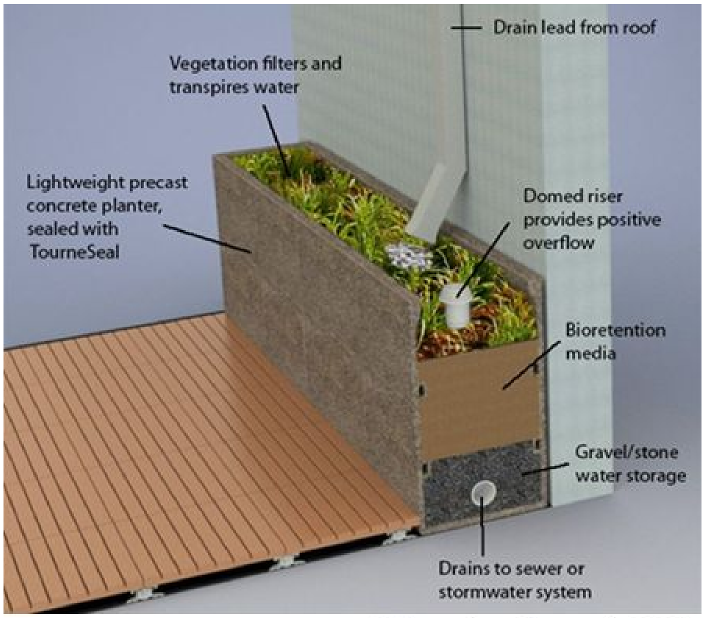
A berm holds water in the garden during heavy rains.

A rain garden and its functions (Cellar Door Home inspection, 2020)

- **Planter Boxes**

Planter boxes are LIDs that mimic rain gardens but are enclosed by vertical walls and perform the function of collecting and filtering stormwater runoff. They can also substantially reduce the volume of runoff entering storm sewers.

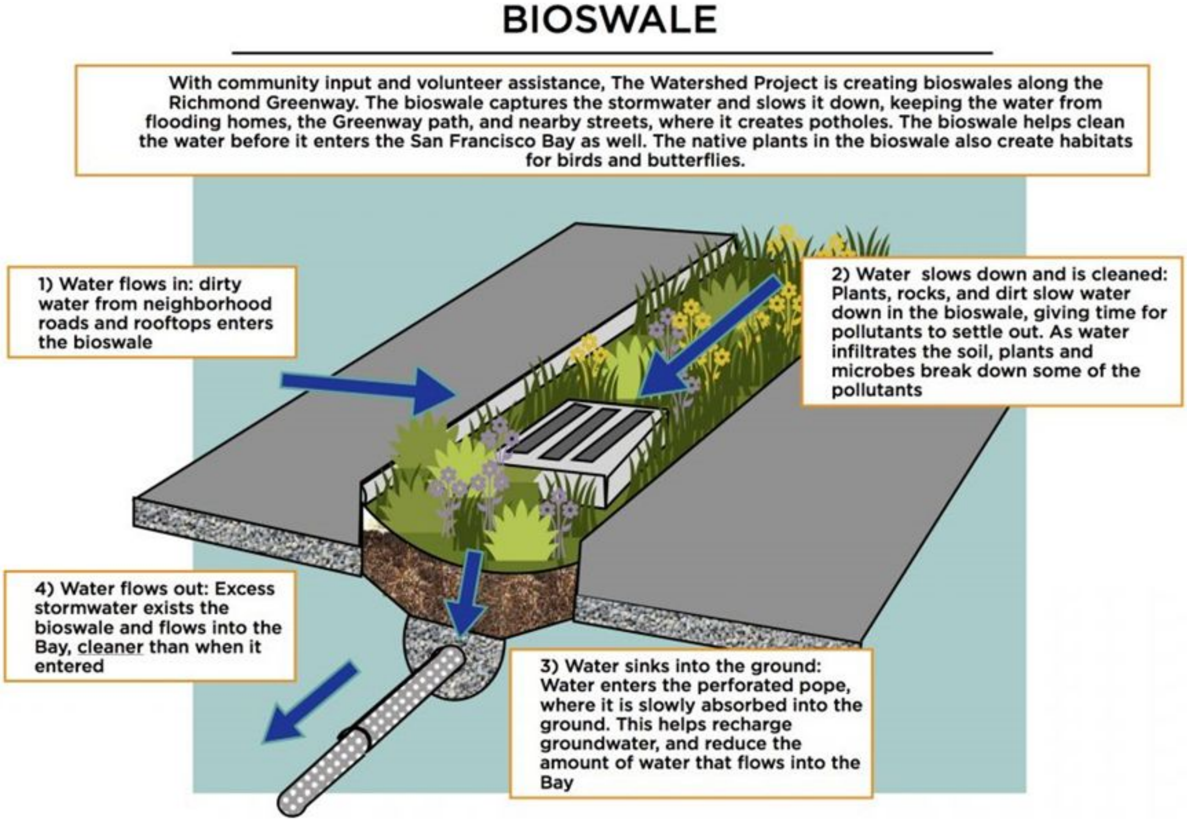
These systems are ideal for space limited sites in dense urban areas and as streetscaping elements.



A planter box (Tournesol, 2020)

- **Bioswales**

Bioswales are designed as channels that perform the function of concentrating and conveying the stormwater runoff and also filtering the debris and other bigger pollutants. Bioswales also help in recharging groundwater. Typical bioswale systems are usually vegetated, mulched or xeriscaped. The side slopes of bioswales are typically less than 6%.



BIOSWALE

With community input and volunteer assistance, The Watershed Project is creating bioswales along the Richmond Greenway. The bioswale captures the stormwater and slows it down, keeping the water from flooding homes, the Greenway path, and nearby streets, where it creates potholes. The bioswale helps clean the water before it enters the San Francisco Bay as well. The native plants in the bioswale also create habitats for birds and butterflies.

1) Water flows in: dirty water from neighborhood roads and rooftops enters the bioswale

2) Water slows down and is cleaned: Plants, rocks, and dirt slow water down in the bioswale, giving time for pollutants to settle out. As water infiltrates the soil, plants and microbes break down some of the pollutants

3) Water sinks into the ground: Water enters the perforated pope, where it is slowly absorbed into the ground. This helps recharge groundwater, and reduce the amount of water that flows into the Bay

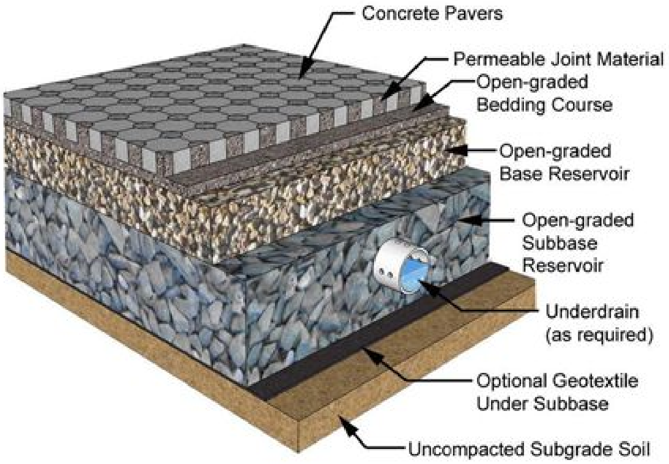
4) Water flows out: Excess stormwater exists the bioswale and flows into the Bay, cleaner than when it entered

A bioswale and its functions (The Watershed Project, 2020)

- **Permeable Pavements**

Permeable pavements are a unique LID system that perform the function of allowing infiltration, treatment, and storage of rainwater. These systems can be made of pervious concrete, porous asphalt, or permeable interlocking pavers.

These systems are cost effective solutions in paved areas where flooding is a common issue.



Permeable pavement (Material Transformations, 2020)

● Green Streets and Alleys with green parking

Integrating green infrastructure into the streetscape of urban areas that perform the function of storing, infiltrating, and evapotranspiration of stormwater. Permeable pavements, rain gardens, planter boxes can be integrated into the street designs. Green parkings are also becoming increasingly popular with permeable pavements and bioswales along the parking lot perimeters. Green parkings also help in mitigating the urban heat island and enhance a walkable built environment in urban areas.

Green streets in Philadelphia (Philadelphia Mayor's office of transportation and utilities, 2014)

URBAN STORMWATER TREATMENT

Stormwater treatment captures pollutants and contaminants from surface water runoff before they reach a watercourse or body of water such as a river, lake or ocean (Hydro International). Structural BMPs are constructed to treat stormwater at the origin or near discharge into receiving waters or urban sewer systems (Wanielista and Yousef, 1993; FHWA, 1996; Dickie et al., 2010; Hvitved-Jacobsen et al., 2010). The removal efficiency of an LID system depends on the type of contaminant present in stormwater and broadly depends on the choice of engineered media in the treatment system, the manipulation of the system's hydraulic behaviour and redox conditions (Grebel et al., 2013) (Appendix 1). Infiltration based LID systems can be amended by using natural or engineered geomedia to meet the criteria of cost effectiveness, availability, and most importantly removing a wide range of pollutants from stormwater during intermittent infiltration of stormwater.

Activated carbon and biochar for stormwater treatment

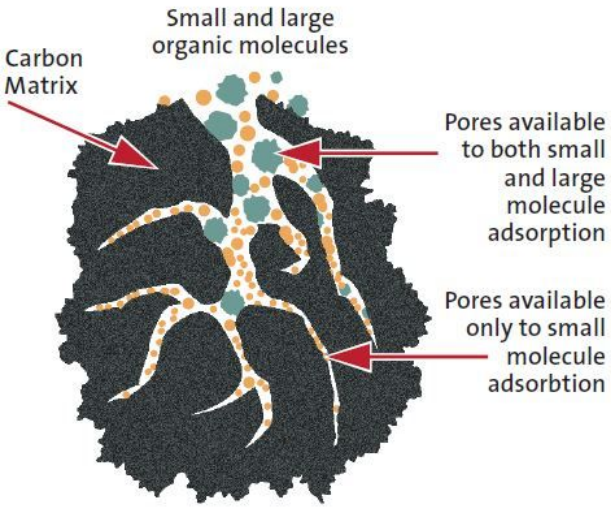
- **Activated carbon (AC)**

Activated carbon is a form of carbon that has small, low volume pores with large surface area (Nagaraju et al., 2012). Properties of activated carbon can be engineered by chemical and thermal processes at elevated temperatures. Chemical processes include impregnation by chemicals (acid, base, or salt) at low temperatures of 250-600℃ and thermal processes include pyrolysis (carbonisation) at 600-900℃ and initial oxidation, followed by steam activation (exposure to oxygen or steam) at 250℃ (Desotec, 2020; Thomas, 2020). Chemical activation is usually preferred due to lower temperatures, better quality consistency, and shorter time for activation. Carbonaceous raw materials commonly used to produce activated carbon are bamboo, coconut husk, willow peat, wood, coir, lignite, coal, and petroleum pitch. Activated carbon is commonly used in methane and hydrogen storage, and as a filter in drinking water treatment. Other applications of activated carbon include air purification, solvent recovery, decaffeination, gold purification, metal extraction, water purification, medicine, sewage treatment, air filters in gas masks and respirators, filters in compressed air, teeth whitening etc.

Types of activated carbon and their properties based on their raw material

Classification	**Raw material**	**Properties**
Powdered activated carbon (PAC)	Crushed or ground carbon particles	Larger surface to volume ratio, allowing for more adsorption
Granular activated carbon (GAC)		Larger than PAC, but have smaller external surface balancing size and surface area.
Extruded activated carbon (EAC)	PAC fused with a binder, extruded into a cylindrical AC block	Low pressure drop, high mechanical strength, low dust content
Bead activated carbon (BAC)	Petroleum pitch	Low pressure drop, high mechanical strength, low dust content
Impregnated carbon	Porous carbon with inorganic	Antimicrobial and antiseptic

	chemicals (iodine, silver, cations such as Al, Mn, Zn, Fe, Li, Ca)	properties help in domestic water purification
Polymer coated carbon	Porous carbon with a biocompatible polymer	Smooth and permeable surface preventing pore blocking
Woven carbon	Rayon fibre	Higher adsorption capacity



Adsorption mechanism in an activated carbon molecule (Elga Veolia, 2020)

- **Activated carbon in stormwater treatment**

Activated carbon is favoured for stormwater treatment opportunities due to their high sorptive affinities for contaminant retention.

1. **Metal removal by Activated carbon**

Metal removal from stormwater by AC depends on metal concentration, contact time, pH, ionic strength, and carbon dose (Anirudhan and Sreekumari, 2011).

Activated carbon type	**Raw material**	**Metal**	**Findings**
GAC	NA	Pb, Cu, Zn Ni, Cd	Removal efficiency in the order Pb, Cu > Zn > Ni, Cd. Other studies show moderate to high removal efficiency. Low As removal efficiency.
	Rice by-products (straw and hulls (husks)) and almond	Cu, Zn	GAC produced from rice by products and almond showed a higher affinity for Cu and Zn compared to the nutshell derived GAC. Almond derived GAC has a higher affinity than other nutshells. Rice based GAC has 14 times and 37 times higher adsorbent capacity
	Nutshell (pistachio,		

	walnut, pecan)		for Cu and Zn respectively.
	Commercial products		Overall greater removal for Cu, but Zn removal lower than laboratory made GACs.
	NA	Cu, Ni, Pb and Zn	Removal efficiency low for Cu and Pb, possibly due to Ni, Cd, and Zn competing for free space in the material structure
AC	Biochar	Hg (II)	Higher sorption than pristine biochar
	Steam-activated coconut buttons	Pb(II), Hg(II) and Cu(II)	Maximum removal obtained at pH 6.0 forPb(II) and Cu(II), and pH 7.0 for Hg(II)

*NA: Information not available

Genç-Fuhrman et al (2007) reported that although GAC (Kemira, Denmark) can effectively remove heavy metals from stormwater, there is a possibility of sorped metal leaching. It is also speculated that AC beds exhaust (saturate) faster as compared to other materials like silica spongolite (SS) and zeolite (Z) when exposed to heavy metals in stormwater (Pawluk and Fronczyk, 2015).

2. CECs removal by Activated carbon

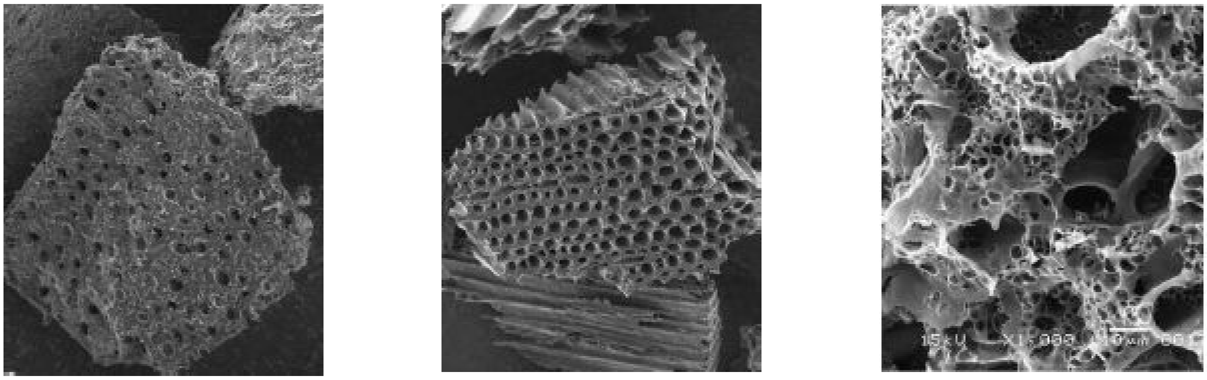
Some CECs can be removed by activated carbon, and their performance is reported in comparison to biochar in the table below.

Activated carbon type	**Organic contaminant/CEC**	**Key findings**	**References**
GAC	Polychlorinated biphenyls, polychlorinated dibenzo-*p*-dioxin/dibenzofurans	2-10% higher removal than biochar	Denyes et al., 2013; Chai et al., 2012
Activated carbon produced from biochar	Atrazine	Sorption capacity 47 times higher than biochar, due to high Brunauer-Emmett-Teller (BET) surface area	Tan et al., 2016
Activated carbon	C-14- Catechol (Catechol is synthetically produced as a commodity organic chemical, mainly as a precursor to pesticides, flavors, and fragrances)	Reduces mineralization of compound, preventing biological degradation in soil	Denyes et al., 2016
	dichlorodiphenyltrichloroethane		
	PAHs	Reduces bioaccumulation twice as much as biochar	Oleszczuk et al., 2017

	Pyrene	Similar removal as biochar	Hale et al., 2011
Sludge based powdered activated carbon (SBAC)	Hydrophobic organic compounds (HOCs) - PAFs, phthalates, alkyl phenols	Amount of HOCs corresponding to 8.5 mg/g SBAC adsorbs on the AC (not in comparison to biochar)	Bjorklund and Li, 2016

- **Biochar**

Biochar is a carbonaceous porous adsorbent, produced typically as a co-product from waste biomass and can last in the environment for decades (Spokas, 2010). Biochar's properties can be controlled by carefully selecting the type of biomass and the production processes. Biochar is produced from biomass under thermochemical processes that include pyrolysis at 300-800℃, gasification, and hydrothermal carbonization (Appendix 2). The biochar pore structure can be retained during pyrolysis, meaning that porosity and pore size distribution depends on the biomass (feedstock). Biochar is commonly used in agriculture, as a soil-amendment. Other benefits of biochar include increase of soil fertility due to improvement of nutrients utilization capacity, carbon sequestration, removal of wastewater pollutants, and remediation of contaminated soil or water (Rajapaksha et al., 2016, Xu et al., 2012).

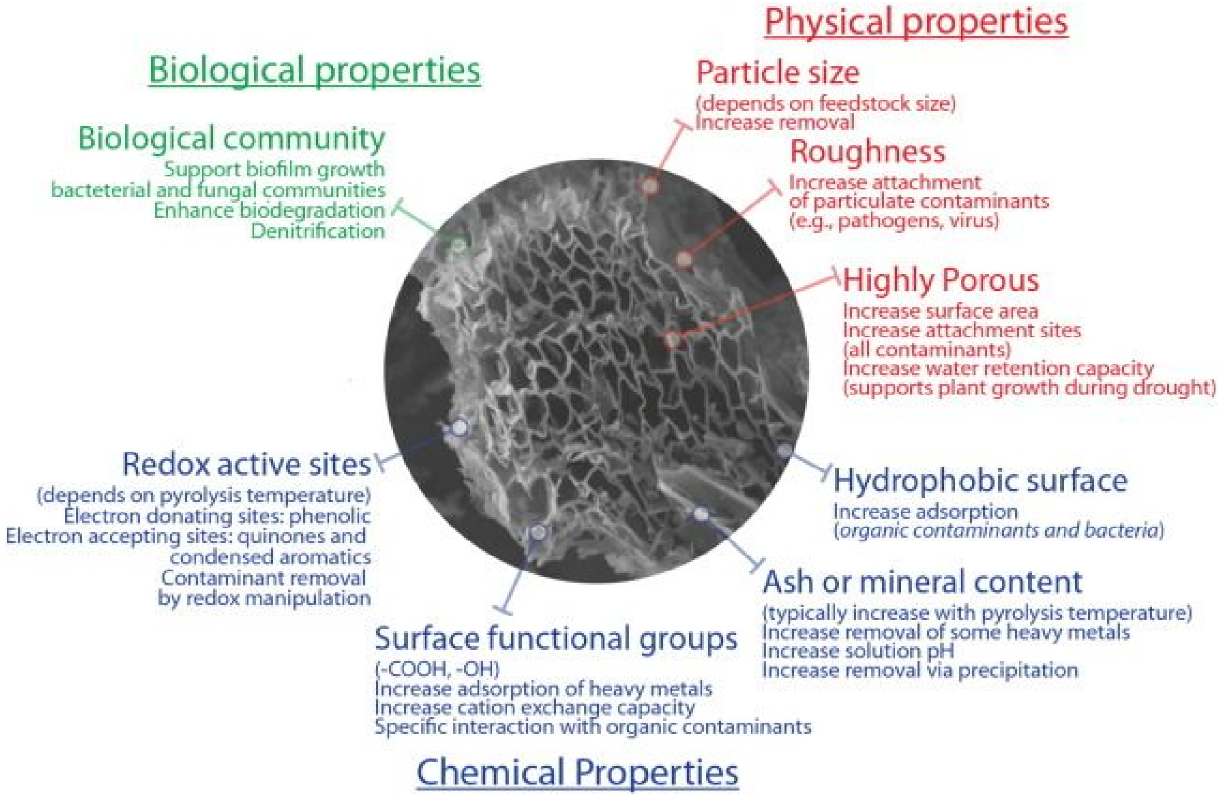

Hazelnut shell biochar Douglas-Fir biochar Cane pith biochar

Different physical composition of biochar based on type of raw material (Tseng and Tseng, 2006)

Types of biochar and their properties based on their raw material

Condition		**Properties**	**References**
Biomass/ Feedstock Type	Softwood derived biochar	More pores in the biochar and higher surface area	Mukome et al., 2013
	Hardwood derived biochar	More dense, and susceptible to thermal decomposition	
	Grass biochar	Higher adsorptive capacity of metals than oak or pine wood biochar	Mukherjee et al., 2011

	Non-wood (grass, sludge, manure) biochar	Lower aromatic and more aliphatic groups, higher ash content (can increase solution pH and decrease solubility of metals/metalloids, thereby increasing removal). Post treatment to oxidise or reduce surface functional groups can change hydrophobicity	Fang et al., 2016
	Manure based biochar	Higher concentration of nutrients, affecting biochar capacity to remove or release nutrients in stormwater	Mukome et al., 2013
Pyrolysis temperature	Higher temperature (500 °C and above)	Pore structure formation affected, micropore volume and surface area of biochar increases. Also has higher hydrophobicity. May result in release of organic and inorganic nutrients.	Ahmad et al., 2012
	Lower temperature (250–350 °C)	Increasing adsorption capacity of cations like metals and CECs	Mukherjee et al., 2011
Biochar activation	Activation by using acid/alkaline solutions, oxidants (Steam, CO_2/NH_3)	Can help expose more pores and increase surface area. Same functionality as an activated carbon, resulting in higher costs.	Rajapaksha et al., 2016



Variation of biochar properties according to their method of production and how they can help in removal of pollutants. From Mohanty et al., 2018

- **Biochar in stormwater treatment**

The use of biochar in stormwater treatment has been explored to some extent. These studies show that biochars are quite effective against the complex conditions of intermittent stormwater events (Nabiul Afrooz and Boehm, 2017, Lau et al., 2017). They can remove different types of pollutants like metals or metalloids, and organics in the presence of dissolved organic carbon (DOC). Like any other geomedia. removal of pollutants by biochar depends on the pollutant characteristics, biochar properties, and treatment conditions.

Based on the pollutant removal mechanisms described in Appendix 2, biochar can enhance pollutant removal by increasing hydraulic conductivity of the soil, and minimizing flooding and increasing storage volume to reduce peak flow. However, there are equal numbers of studies that also suggest that biochar decreases the hydraulic conductivity of soil. The difference in particle size between the biochar and soil and hydrophobicity of biochar may be the reason for the decrease. Particle size of biochar is an important design criteria to ensure less clogging in the treatment system. For LIDs that have submerged media layers, porous material like biochar can increase anoxic water storage in the internal pores and create isolated reducing zones. Surface functional groups on the biochar like electroactive quinoid functional groups and polycondensed aromatic sheets are redox active and can oxidise and reduce attached contaminants (Klupfel et al., 2014). Biochar can also act as microbial electron acceptor or donor to facilitate microbial degradation of contaminants via redox cycling (Saquing et al., 2016).

Removal of any contaminant (%) is based on a breakthrough curve ($1 - C / C_0$), where C and C_0 are effluent and influent concentrations, respectively. If 100% breakthrough (exhaustion of biochar) was achieved during the experiment, the removal was reported as capacity (mg of contaminants per gram of biochar).

1. **Metals removal by biochar**

Metals can be adsorped on biochars that are rich in deprotonated carboxyl and sulfonic groups. Most removal mechanisms reported in studies have been done in bench scale works and are expected to behave similarly in LIDs. A table describing the performance of different biochars in metal removal is shown below:

Biochar type	**Metal**	**Removal/ adsorptive efficiency**	**Findings**	**References**
H_2O_2 activated peanut hull hydrochar	Ni^{2+}, Ca^{2+}, Cu^{2+}, Pb^{2+}	0 -30%	Activation enhanced the metal sorption capacity of biochar. Removal was in the order: $Pb^{2+} > Cu^{2+} > Cd^{2+} > Ni^{2+}$	Xue et al., 2012
Wood pellet biochar from gasification	Cd^{2+}, Cr^{6+}, Cu^{2+}, Pb^{2+}, Ni^{2+}, Zn^{2+}	18-75%	Amount of oxygen functional groups, oxygen to carbon ratio, pH and acidity impacted removal	Reddy et al., 2014
Hickory wood biochar modified with NaOH	Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}, Ni^{2+}	11–54 mg/g	Less effective in removing Cd^{2+}, Zn^{2+} and Ni^{2+}	Ding et al., 2016

Chicken bone biochar	Cd^{2+}	3.5–13.4 mg/g	Adsorption efficiency were higher at lower loading rate	Park et al., 2015a
Teak leaves biochar	Ni^{2+}, Co^{2+}	7-27 mg/g	Filter media depth impacted bed adsorption capacity	Vilvanathan and Shanthakumar (2017)

2. CECs removal by biochar

Removal of most of these compounds by biochar occurs via several processes including sorption. The mechanisms of sorption include π-π electron donor acceptor (EDA) interaction, hydrogen bonding, and hydrophobic attraction for non-ionic organics, as well as electrostatic attraction for ionic organics, based on surface polarity of biochar.

Biochar	**Organic pollutant/CEC**	**Removal**	**Findings**	**References**
Buffalo weed biochar-alginate beads	2,4,6-Trinitrotoluene (TNT), 1,3,5-trinitro-1,3,5-triazacyclohexane (RDX)	2.7–20.2 mg/g	Feed (wastewater) concentration impacted adsorption of TNT and RDX	Roh et al., 2015
Magnetic activated sawdust hydrochar	Tetracycline	423 mg/g	Stable adsorption of tetracycline was achieved inspite of pH variability (5-9)	Chen et al., 2017b
Fe-impregnated biochar	Chlorpyrifos, endosulfan, fenvalerate, diuron (Pesticides)	45–100%	In combination with a constructed wetland with *Cyperus alternifolius* plant, attained high removal of pesticides by adsorption and microbial degradation	Tang et al., 2016
Biochar-amended silty clay	Pentabromodiphenyl ether (BDE-99)	77.2–100%	BDE-99 was removed by anaerobic degradation by the archaeal community in the biochar amended soil. As the recharge time and filter depth increases, removal mechanisms changed from adsorption to biodegradation.	Yan et al., 2017
Soybean stover biochar (BC; pyrolyzed at 300 °C or 700 °C)	Trichloroethylene (TCE)	36–515 mg/g	Removal slightly lower at 700 °C compared with activated carbon.	Zhang et al., 2015
Biochar (0.5	Several trace organic	NA	Biodegradation of trace organic	Ulrich et al., 2017a

wt%) with soil/sand	contaminants including atrazine and methylbenzotriazole.		pollutant higher when compost was added to the biochar augmented soil	

3. Nutrients removal by biochar

Most column experiments researching removal of nutrients by biochar have been useful to estimate sorption capacity and mechanism of nutrient removal. However, these results have not been able to be replicated on the field.

Biochar	**Nutrient**	**Findings**	**References**
Wood-based biochar and sand mixture (3:7) by volume	29.2–64.8% for NO_3^-, 50–58 % for NH_4^+	Nitrate removal increased in a submerged layer, but no impact on ammonium removal	Nabiul Afrooz and Boehm, 2017
Poultry litter biochar and Hardwood biochar 10% (w/w) biochar mixed with sand	92–96 % for NH_4^+	Greater ammonium removal capacity observed in biochar amended soils as compared to sand-only columns.	Tian et al., 2016
Biochar amended wood chips	32–100 % (TN)	Improved TN removal capacity compared to only wood chips. Also reduced costs of removing nitrogen.	DeBoe et al., 2017
70.0% agricultural char & 30% char from passenger car tires 7% (w/w) biochar	26–97 % for NO_3^-, 1–43 % for PO_4^{3-}	Usage on the green roof with biochar can improve runoff water quality and retention	Beck et al., 2011
Biochar feedstock from birch wood (including bark) 7% (w/w) biochar	5–24 % for TN, 21–27 % for TP	Studies show contradictory removal efficiencies, and is depended on media and plant properties used in the green roof	Kuoppamaki et al., 2016
Pinewood (6.7 wt%, 33 vol%)	86 % for TN, 68 % for NO_3^-	About 60% more removal of TOC, TN, NO_3^-, and TDP due to biochar amended biofilters in 6 months operation	Ulrich et al., 2017a
Bamboo charcoal 0.5% (w/w)	15.2 % for NH_4^+–N	Vertical mobility of NH_4^+–N slowed in soil column	DIng et al., 2010
Monterey pine-sawdust	40–80 % for NH_4^+–N	Leaching of NH_4^+–N reduced with amendment of soil using pine and pine waste biochars. Nitrate	Paramashivam et al., 2016

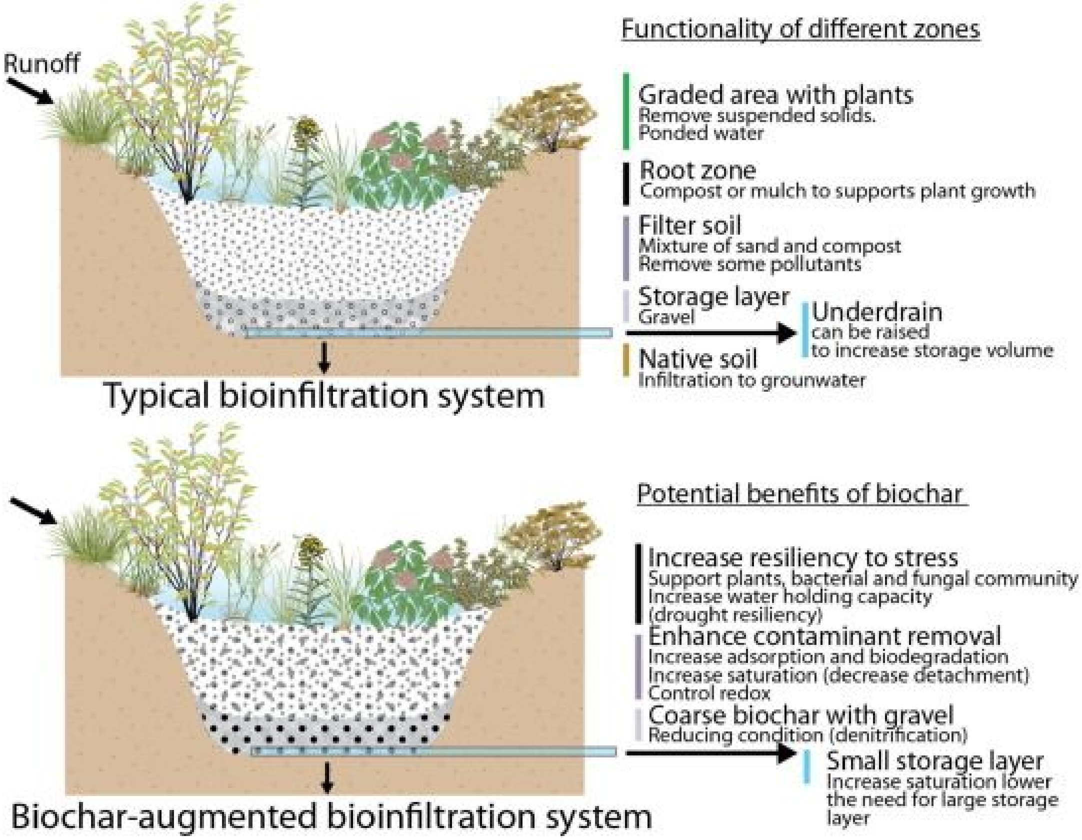
biochar; pine biochar; pine waste biochar		leaching was not impacted.	

IMPACT OF AC & BIOCHAR IN URBAN STORMWATER LID

Currently, most urban stormwater LID systems aim to achieve four main objectives (Chris Johnston, 2020):

- To ensure that the stormwater runoff or effluent meets water quality guidelines imposed at site. The main contaminants in stormwater runoff are total suspended solids (TSS) and nutrients.
- To reduce the volume of stormwater being relayed to the sewer networks. This is to ensure that ponding and waterlogging problems can be mitigated through the LID systems
- To control the rate of stormwater flowing into the groundwater storage. This is to ensure that enough transpiration, evaporation, and evapotranspiration of the water can occur to balance the water cycle before it flows into groundwater storage.
- To ensure that there is a safe passage of the runoff during a high intensity storm event.

The performance of the stormwater management systems can be enhanced by using different filter media like AC and biochar that offer benefits of not only water volume reduction but removal of established and newer contaminants of concern in stormwater runoff.



Advantages of amended bioinfiltration systems using biochar (Mohanty et al., 2018)

Based on laboratory studies, the potential benefits of using AC or biochar media in stormwater management systems can be as described in the table below:

LID system for stormwater management	**Potential benefits of using AC or biochar filter media**
Downspout filter boxes	Removal of contaminants like nutrients, organic chemicals, and supporting growth of plants by water retention and slow release of nutrients.
Bioinfiltration system or bioretention systems (rain gardens/planter boxes)	Support for plant growth through water retention and slow release of nutrients, and increased removal of contaminants
Bioswales	
Infiltration trenches	Increased removal of hydrocarbons, metals,TSS, and toxic organics

COMPARISON BETWEEN AC & BIOCHAR

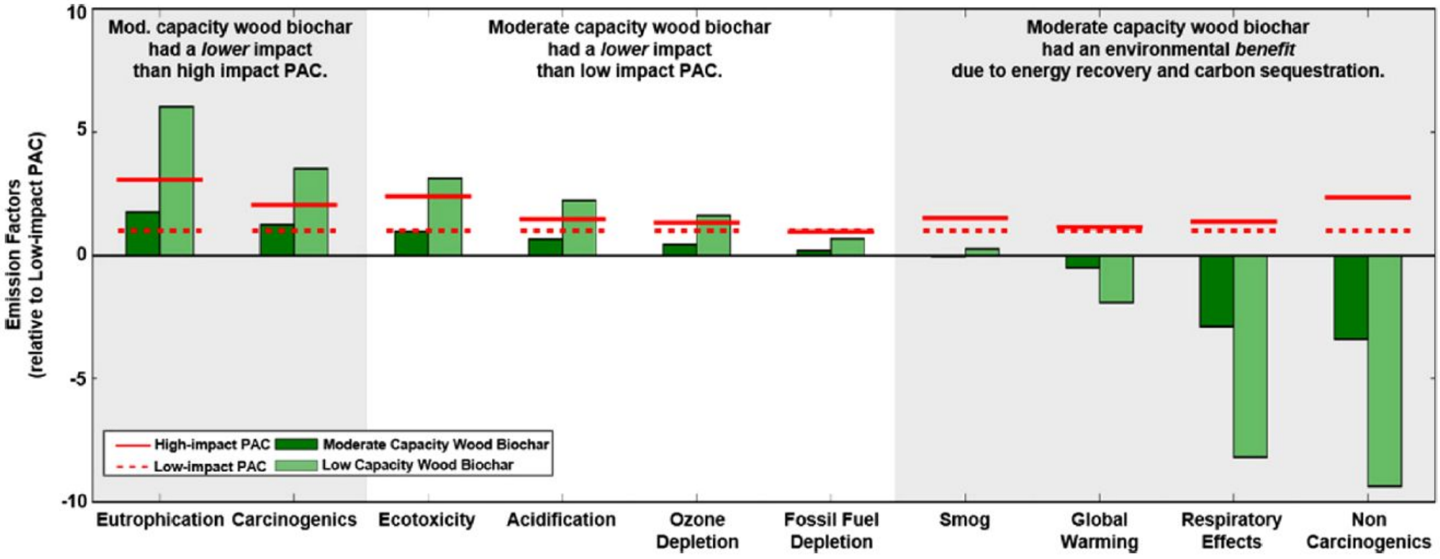
Activated carbon (AC) has been established as a viable and effective filtration media for drinking water and wastewater treatment. Biochar's viability as a filtration media has been recognized widely only recently. The physical and chemical properties of AC and biochar can be modified according to their feedstock and production methods. Comparatively, the main difference lies in the overall cost and production or activation processes involved. However, some comparisons can also be made based on their environmental and economic performance, as discussed further in this section.

- **Environmental impact comparison between AC & biochar**

Elkhakufa et al., (2019) performed a review on the environmental impacts of the pyrolysis processes and application of the biochar. The pyrolysis of biomass generates fuel gases and oils containing lower hydrocarbons, lower olefins, carbon dioxide, carbon monoxide and water vapour. Only a fraction of this fuel can be reused for initiating pyrolysis, the remaining fraction can be used for electricity generation, process heating, or chemical production. The application of biochar to soil has several benefits of soil enhancement, improved water retention and nutrient holding, amongst others. Overall, the impact from generation and application of biomass derived biochars is assumed to be positive. According to Spokas et al., (2012), application of biochars with typical carbon contents of 10% and 50% and depending on pyrolysis conditions can sequester carbon. Other studies suggest that there might be a small release of carbon dioxide mostly from the consumption of labile carbon in biochar by the microbes in soil (Zimmerman et al., 2011). GHG values amounting to 10-20% of the biochar carbon production can be expected to be released. According to Elkhakufa et al., (2019), this wide range is due to variability in feedstock type, pyrolysis time and temperature, soil pH and characteristics, and finally the climatic conditions of the site. Changing process conditions to high temperature and long reaction time in an effort to rescue labile organic carbon can reduce some of the GHG emissions. However, this may lead to a lower yield and requires the need for optimization studies.

Thompson et al (2016) conducted a life cycle assessment to compare 10 environmental impacts from the production and use of wood biochar, biosolids biochar, and coal-derived powdered activated carbon (PAC) to remove sulfamethoxazole, a personal care product (CEC), from wastewater.

PAC has been identified as a viable adsorbent for removal of this CEC from wastewater with lower environmental impacts as compared to other technologies like reverse osmosis and ozone or UV light oxidation. Negative environmental impacts of PAC include emissions due to its production from coal and high energy activation processes required for property modification. Comparatively, biochar has also shown sorption capacities for some CECs like agrichemicals, pharmaceuticals, and personal care products (PCPs) and other endocrine disrupting compounds. The cost of biochar is also quite low as compared to PAC (on a mass basis) and certain environmental benefits like energy co-production, carbon sequestration, and bio waste reuse and recycling by using agro-wastes exist for biochar.



Relative environmental impacts for the studied scenarios (Elkhakufa et al., 2019)

For PAC, the negative impacts were due to emissions from PAC generation and transportation to the wastewater treatment facility. Opportunities for lowering the overall environmental impact exists in decreasing the energy usage during generation and reducing the distance of transportation. Additionally, biomass based ACs (wood or coconut based ACs) may be better to reduce environmental impacts by carbon sequestration.

For Wood biochars from pine wood, significant environmental benefits and lower environmental impacts compared to PAC were identified. Positive environmental benefits were due to carbon sequestration and energy production from pyrolysis. The estimated net amount of carbon sequestration for moderate capacity wood biochar was 0.57 kg CO2 equivalent (eq) per kg dry feedstock and for low capacity wood biochar was 0.67 kg CO2 eq/kg dry feedstock. Considering the LCA methodology, energy recovered from pyrolysis offsets the energy produced from wood chip combustion, which was the protocol used at the full-scale wood biochar and wood pellet co production facility before the installation of pyrolysis energy recovery infrastructure. The estimated energy recovered during the production of moderate capacity wood biochar was 8.6 MJ heat/kg dry feedstock and 7.5 MJ heat/kg dry feedstock for low capacity wood biochar. The energy produced as a percent of feedstock heat content was 44% and 38% for moderate and low capacity wood biochars. Negative environmental impacts are emissions from the pyrolysis gas combustion, wood chip generation, and electricity use.

For biosolids biochar, some negative environmental impacts were the emissions from the energy required for generation and drying of the feedstock. Due to the hybrid nature of biosolids biochar in this study (combined with PAC and wood based biochar), some opportunities for energy offsets are through using pyrolysis heat for wood chip combustion, when biosolids biochar is combined with wood chip based biochar.

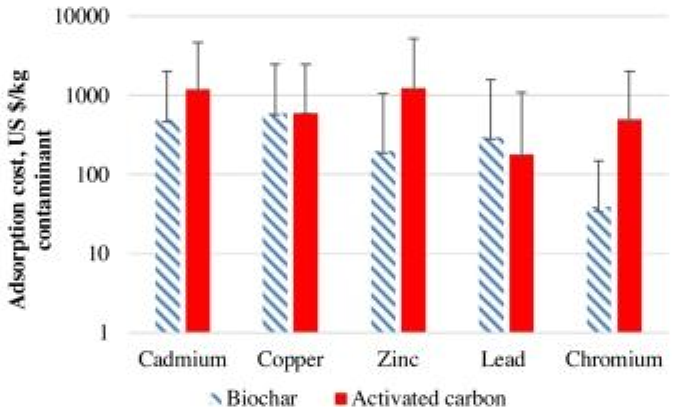
Overall, Thompson et al., (2016) concluded that wood biochar can be an environmentally sustainable adsorbent for removal of trace organic pollutants of SMX. The moderate capacity wood biochar scenario sequestered enough carbon (about 6.5 gigagrams CO2 eq./yr) to offset all of the wastewater treatment plant's (WWTP) carbon emissions from energy and chemical use (about 5.0 gigagrams CO2 eq./yr. for a 12.5 mgd facility, assuming 0.29 kg CO2 eq./m3 for a WWTP that has organics and nutrient removal).

- **Economic performance comparison between AC & biochar**

Alhashimi et al., (2017) assessed the economic performance of biochar as compared to AC for removal of heavy metals. Adsorption capacity and commercial price of each material were used for the comparison based on ‘effective adsorption cost’, which correlates the amount of adsorbent required to adsorb a unit of heavy metal.

Economic costs comparison between AC and biochar

Heavy metal studied	**Adsorption costs per unit of heavy metal**	
	AC	**Biochar**
Copper	Around $600/kg of copper	
Lead	$180/kg of lead	$300/kg of lead
Zinc	$1240/kg of zinc	$200/kg of zinc
Chromium	$500/kg of chromium	$40/kg of chromium



Cost Comparison between AC and biochar (Alhashimi et al., 2017)

The average cost of activated carbon and biochar were estimated to be $5.6/kg and $5/kg respectively. Overall, considering the metals considered, biochar was found to be less costly than AC. However, Alhashimi et al., (2017) concludes that this comparison must be evaluated on a case by case basis, depending on the availability of the biochar from the raw materials, and the contaminant or material mix to be adsorbed. Some uncertainties exist in biochar properties and the varying market prices for commercial products.

The following table compiles some comparisons between AC and biochar, compiled from the present state of research.

Brief comparison between AC and biochar compiled from available literature

Comparison criteria		**AC**	**Biochar**	**References**
Cost (CAD/metric ton)*		1472 - 2275	468 - 1606	Thompson et al., 2016
Energy demand (MJ/kg)		97	6.1	Alhashimi and Aktas (2017); Thompson et al., 2016
Greenhouse gas emissions (kg CO_2 eq/kg)		6.6	-0.9	
Surface area		High	Lower than AC irrespective of feedstock and production process	Tan et al., 2016
Biomass yield in amended soil		Low	High	Brendova et al., 2016
Performance with metals	Cd uptake in amended soil	Low	High	Brendova et al., 2016
	Cr and Zn removal	Low	High	Alhashimi and Aktas (2017)
	Hg (II) adsorption	Low	High	Tan et al., (2016); Xu et al., (2016)
Performance with CECs	Bioaccumulation of PAHs in plants	Low	High	Oleszczuk et al., 2017
	Polychlorinated dibenzo-p-dioxin/ dibenzofurans removal	High	Low	Chai et al., 2012
	Polychlorinated biphenyl adsorption	High	Low	Denyes et al., 2013
	Dichloro-diphenyltrichloro-ethane (*DDT*) accumulation	High	Low	Denyes et al., 2016
	Pyrene removal	Low	High	Hale et al., 2011
	Mineralization of C-14-catechol	High	Low	Shan et al., 2015
	Trace organic contaminants removal	Low	High	Ulrich et al., 2017a
	Atrazine adsorption	High	Low	Tan et al., 2016

Chemical oxygen demand removal	Low	High	Huggins et al., 2016
Dissolved organic carbon removal	High	No effect	Oleszczuk et al., 2017
Soil toxicity towards *Vibrio fischeri* and *Folsomia candida*	Low	High	Koltowski and Oleszczuk, 2016
Lowered toxicity	Low	High	Hale et al., 2011
Inhibition of seed germination	Low	High	Josko et al., 2013

*1 USD = 1.34 CAD, as on Aug 7, 2020

*High indicates better performance than, Low indicates poorer performance than.

*-ve sign indicates negative values for GWP associated with biochar production due to carbon abatement ability of biochar

APPLICATION

CASE STUDIES

Feasibility studies and pilot scale studies can offer valuable information on the current state-of-the-art application of activated carbon and biochar in stormwater treatment. Case studies from the US Biochar initiative (UBI) have been described in this section based on two main themes: Media for soil amendment, and Pollutant removal.

Media for soil amendment

Case studies included in this section mainly focus on the use of biochar media for amending soil properties with the main objective of reducing nutrient leaching, and improving water retention and infiltration for stormwater runoff

1. **Application of biochar for soil amendment to reduce nutrient leaching**

Sigua et al (2016) studied biochar amended soils on their ability to reduce nutrient leaching and improve soil chemical properties.

Study Objective

- To evaluate the biochar amended soil on nutrient leaching and improving soil water retention

Study Methodology

Biochar media	2 types of biochar from feedstock in pelletized form (10-20 mm in length, 6-8 mm in dia) produced through slow pyrolysis at 500℃. ● Pine Chips biochar (PC) ● Poultry litter biochar (PL)	
Greenhouse experiment	Biochar media	4 different blends of biochar media were used: ● 50:50 blends of PC and PL ● 80:20 blends of PC and PL ● 100% PL
	Methodology	Biochar rate of application ar 40 Mg/ha (biomass) (2%); performance evaluated through Winter wheat irrigation
	Result	● Biochar amended soils had different total nitrogen but no change in total carbon; 100% PL had the greatest TN in the soil ● Soils with 50:50 PC:PL and 100% PL showed an increase in P, K, Ca, and Mg concentrations by 669%, 830%, 307%, and 687%, compared to a control
Leaching Study	Biochar media	Same as greenhouse experiment
	Methodology	Biochar rate of application ar 40 Mg/ha (2%)

	Result	Water retention was higher in the soils amended with 50:50 PC:PL, 80:20 PC:PL, 100% PC (by 133%, 77%, and 41% respectively), compared to 100% PL and control

Conclusion

- Significant water retention can be possible in biochar amended soils, with the most preferable blend being the 50:50 PC:PL. Soil fertility can also be increased with biochar amendment.

2. Application of biochar for soil amendment for mine remediation

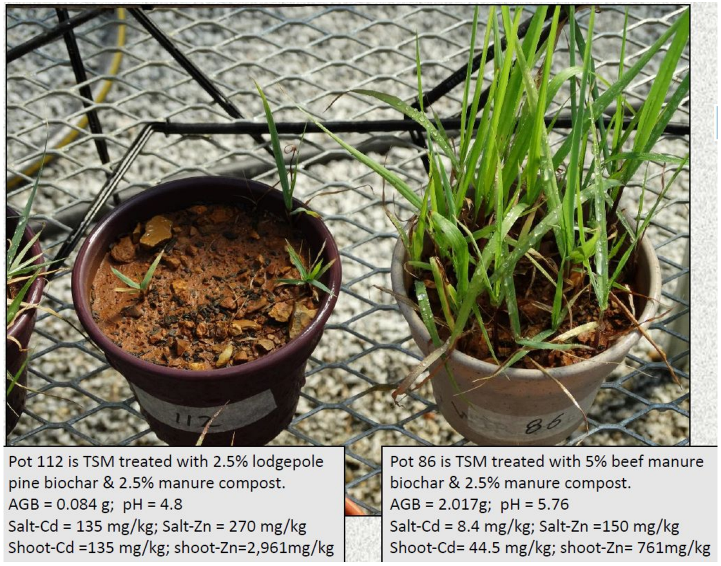
Novak et al (2018) studied the application of ‘designer’ biochar for soil improvement, greenhouse gas sequestration, metal, and nutrient sequestration in North and South Carolina, South east Coastal Plain, that inherently have problems with poor fertility, acidic pH, and low soil organic carbon.

Study Objectives

- To select the appropriate biochar blend from a selected number of biochars
- To determine the application rate, morphology, and application method of biochar

Study Methodology

<table>
<tr><td rowspan="1">Study area</td><td colspan="2">● Formosa mine site (FMS)- problems of acid mine drainage, poor microbial activity, erosion issues, and poor soil-plant relationships.
● Tri-state mine site (TSM) - problems of mine waste storage on site, sporadic plant cover, chemical and physical issues, and heavy metal concentration (Zn and Cd) in the soil.</td></tr>
<tr><td>FMS remediation</td><td colspan="2">● Phase I: 120 holes were dug on the soil, and these holes were filled with layers of biochar, biosolids, and lime.Pine trees were planted on the holes, and a pine tree plantation was aimed to be established
● Phase II: A bigger plot of land was prepared for amending with biochar and grasses or forbes were planted.</td></tr>
<tr><td rowspan="3">TSM soil remediation</td><td colspan="2">Issues: High heavy metal concentration - Cu, Cd, Zn</td></tr>
<tr><td>Goal</td><td>To identify biochar blends suitable for a switchgrass growth experiment</td></tr>
<tr><td>Biochar</td><td>4 types of media blends including 3 different types of biochars were used:
● Lodgepot pine biochar
● Poultry litter biochar
● Beef cattle manure biochar
● Beef cattle manure compost</td></tr>
</table>



Pot 112 is TSM treated with 2.5% lodgepole pine biochar & 2.5% manure compost.
AGB = 0.084 g; pH = 4.8
Salt-Cd = 135 mg/kg; Salt-Zn = 270 mg/kg
Shoot-Cd =135 mg/kg; shoot-Zn=2,961mg/kg

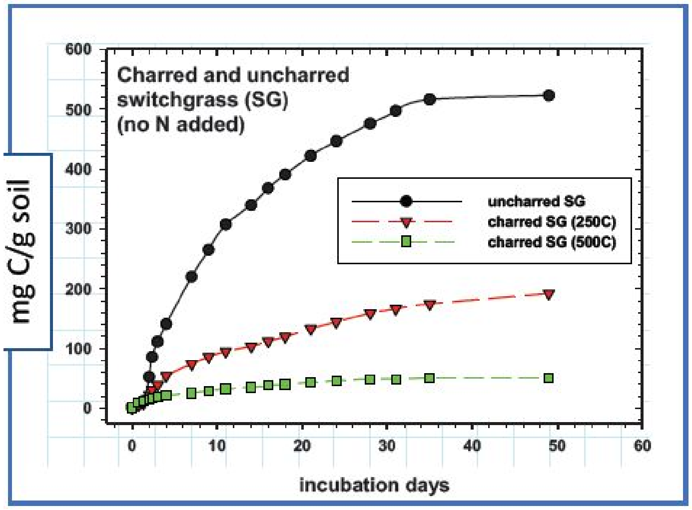
Pot 86 is TSM treated with 5% beef manure biochar & 2.5% manure compost.
AGB = 2.017g; pH = 5.76
Salt-Cd = 8.4 mg/kg; Salt-Zn =150 mg/kg
Shoot-Cd= 44.5 mg/kg; shoot-Zn= 761mg/kg

Results of the switchgrass experiment (Novak et al., 2018)

Conclusion

- The identification of the right biochar blend for a soil type depends on the soil chemistry, and designer biochars can be made to target the chemistry associated with the soil deficiency. Hence, soil studies are important.

- Most of the greenhouse gas emissions from biochar are associated with the production stage.



Correlation between carbon sequestered and incubation days (Novak et al., 2018)

According to Novak et al., (2018), for biochars that are produced by high temperature pyrolysis, significant GHG emissions can be expected. Further, these types of produced biochars have an undesirable chemical structure that is resistant to microbial oxidation and conversion to CO2, making them less biodegradable and hence, have lower ability to sequester carbon. Hence, it may be concluded that high-temperature pyrolysis biochars donot have similar environmental benefits to low-temperature pyrolysis biochars. Overall, although there is potential on using biochar for soil amendment, considerations are required for the environmental impacts of biochar production and application.

3. Application of biochar amended soil for stormwater management

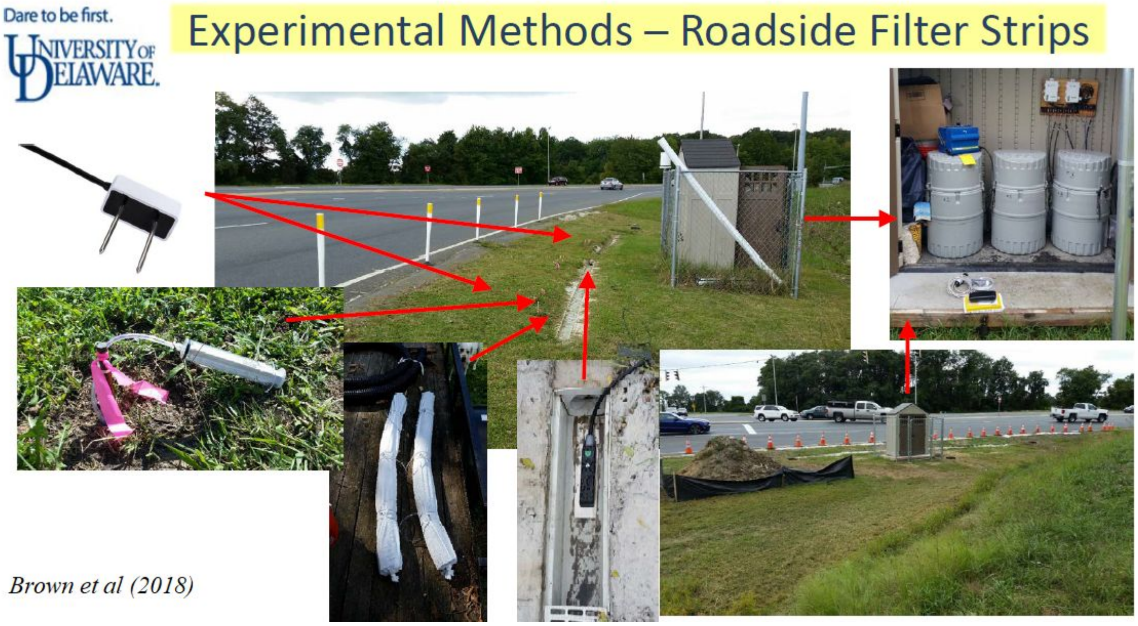
Brown et al (2018) from the University of Delaware conducted a field study in Delaware on the performance of a biochar amended soil as a part of stormwater management. A strip of land consisting of only soil (as control) was compared with another strip of land consisting of 4% biochar amended soil.

Study objectives

- To assess the impact of biochar amended soil on water retention and infiltration

Study Methodology

Biochar	Pinewood Biochar pyrolysed at 550℃.
Results	Compiled from 123 rain events, biochar amended strip land reduced runoff flow rate and stormwater runoff volume by 56% and 69% respectively.

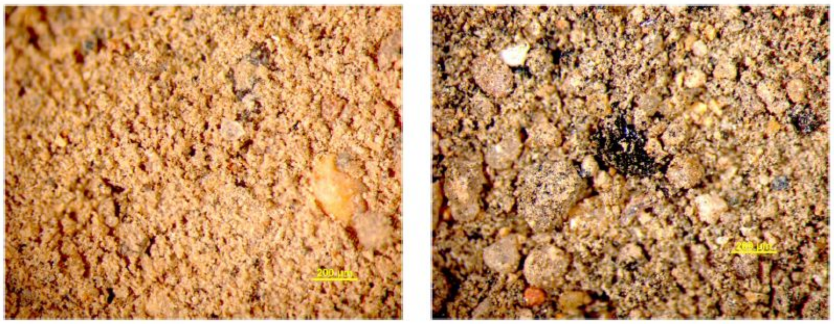


Dare to be first. University of Delaware

Experimental Methods – Roadside Filter Strips

Brown et al (2018)

Dissecting Microscopic Imagery



Existing Soil

Existing Soil with 4% Biochar

Conclusion

Significant improvements were observed in overall stormwater runoff rate and volume reduction in the biochar amended soil. Hydraulic conductivity of the biochar amended soil was also higher than the control soil.

Media for pollutant removal

Case studies included in this section mainly focus on the removal of metals, nutrients, and CECs including trace organic compounds, agricultural wastes and pesticides, pharmaceuticals (uptake and removal).

4. Port of Townsend Biochar Stormwater Feasibility Study

In 2011, Port of Port Townsend (PoPT) Boat Haven Facility in Washington reported excesses of several heavy metal concentrations in stormwater runoff, according to the Washington State Department of Ecology Boatyard General Permit for Stormwater Discharge. A waste based biochar produced from burnt wood chips biomass from the Port Townsend Paper Company (PTPC) located 1 mile from the PoPT was used as the principle biochar source.

Pilot scale Downsprout filter at the PoPT facility (Gray et al., 2015)

Study objectives

- To assess the feasibility and effectiveness of using biochar for elevated heavy metal (copper and zinc) concentration reduction in stormwater runoff at the facility
- Reduce environmental compliance costs for the facility due to the low cost of biochar as compared to other treatment technologies
- Reduce waste generation by diverting byproduct waste from landfills towards reuse as a filter media
- Add to current knowledge base of biochar as a stormwater treatment filter media option

Study Methodology:

Laboratory Testing	Biochar type	8 biochar and soil mixtures were made and screened for their basic properties (conductivity, pH, ash content, organic carbon etc). Screening of mixtures done to assess heavy metal removal efficiency and probability of leaching of materials into runoff.
	Stormwater	Synthetic stormwater with zinc and copper added to produce a high and low concentration mixtures similar to concentrations in roof and surface water runoff at the facility

	Results	● High copper removal and variable zinc removal in all types of biochar and soil mixtures ● Hydraulic flow rates around 3.3 inches/min to 10.9 inches/min
	Conclusion for pilot scale	● Material flow rate adopted for pilot scale > 5 inches/min based on results for Mixture #8 ● Mixture #8 - biochar and compost chosen due to greatest contaminant removal (98.5 - 99.8 % for copper and 97.6 - 98.9 % for zinc) and good media conductivity (3.3 inches/minute for the mixture).
Pilot scale installation on site	Testing apparatus	Biochar ‘tote’ - custom designed biochar downspout filter and an existing in-ground sand filter retrofit.
	Biochar type	Mixture 8 biochar + compost media from the laboratory tests was rinsed and sieved, and packed into a media bed.
	Technology	Upflow filtration to increase filter longevity and reduce media clogging by opposite flow direction to gravity flow.
	Stormwater	Roof runoff had high zinc concentration of 4120 µg/L, copper concentration of 64 µg/L, and phosphorus concentration of 0.02 µg/L
	Results	Biochar tote had removal efficiencies of 95.4% (average) for copper and 99% for zinc. Surprisingly, the concentration of phosphorus in stormwater runoff increased dramatically to around 1.12 µg/L (possibly from the compost).
Feasibility Study	Installation	Installation of biochar and compost totes in parallel within a larger stormwater management strategy: ● 18 biochar totes for high zinc rooftop stormwater runoffs ● 2 biochar secondary filtration devices (SFDs) to treat effluent of StormwateRX Aquip (a enhanced stormwater filtration system from StormwaterRX, approved by the Washington Department of Ecology with a Conditional Use Level Designation (CULD) for Phosphorus treatment) surface water treatment units ● 2 custom built in-ground filtration vessels using biochar media
	Biochar type	80% rinsed Biochar + 20% pelletized peat mixture used instead of biochar and compost due to concerns with the increase of phosphorus concentration in the runoff. Volume of biochar-peat media was about 20 m3.
	Technology	Same as pilot scale
	Stormwater	A single 2014-2015 rainy season, which had below normal precipitation and consequently lower runoff.
	Results	Biochar uplow totes removed about 80% of copper and 94% of zinc, from 4 sampling events.
	Conclusion	● Due to the short nature of the pilot scale study, biochar based infiltration was deemed effective only for a short term, and their viability over multiple

		seasonal changes is yet to be looked into. ● Design of the system is also important, as the totes performed better than the SFDs and the custom in-ground vessels. ● Due to concerns of clogging, all except one biochar media was rinsed thoroughly with water. Flow seems to decrease over time as finer sediments accumulate within the filter media. If unrinsed, as done with one control tote, there is an increase in copper and zinc in the stormwater effluent in two months. ● The study acknowledges that the blend of biochar and peat was very specific for the location, and for similar application in another place, the corresponding blend and type of biochar needs to be decided on.

5. Study by Oregon State University (OSU)

A collaborative study by Oregon State University (OSU), Oregon Best, Sunmark, and bioLOGICAL solutions aimed to develop media particularly for copper and zinc removal.

Study objectives

- Obtain a suitable biochar from available sources and the ideal processing requirements
- Create and assess media blends using the suitable biochar and secondary components that may be inert (sand, gravel, pumice), organic (coconut coir, peat, compost), and reactive (zeolites, activated carbon)
- Characterize complete filtration blends that offer benefits of contaminant removal, good filter, hydraulics, pH, toxicity etc.

Study Methodology

Preliminary testing	Biochar type	7 different biochar blends were tested
	Stormwater	Synthetic stormwater samples were used
	Results	About 88-90% copper and a variable zinc removals obtained
	Conclusion	A 75% biochar + 25% pelletized peat biochar blend was chosen to be used for the subsequent column testing.
Column testing through Rapid Small Scale Column Tests (RSSCTs)	Biochar type	75% biochar + 25% pelletized peat biochar
	Stormwater	Real stormwater samples
	Conclusion	Around 90% copper removal was obtained, but zinc removal was quite varied. However, biochar supplemented by pelletized peat biochar can dramatically improve zinc removal as compared to only supplement with only peat.

6. Bioretention media study by Herrera Consulting

A collaboration between Herrera Environmental Consultants and Kitsap County to improve bioretention soil media performance for the capture and retention of nitrogen (N), phosphorus (P), and copper (Cu) commonly present in stormwater. As per the 2012 Western Washington Stormwater Management Manual (Ecology 2014), a typical bioretention system in Western Washington should consist of 60% sand and 40% compost. However, there is possibility of nutrient and metal leaching from these systems. The media blends described hereafter refer to different blends of biochar.

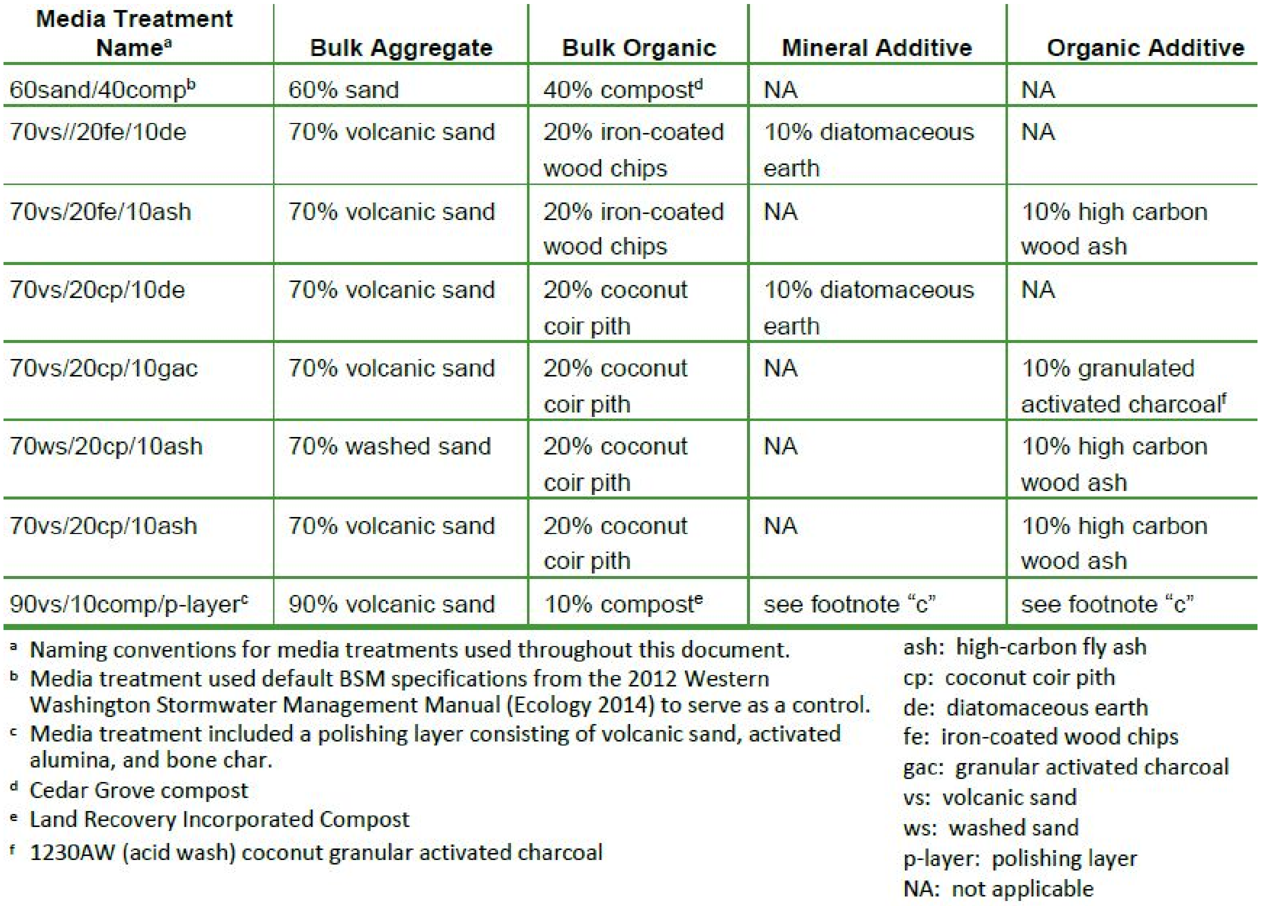
Study objectives

- Get a perspective on potential bioretention media components based on pollutant capture capability, cost, availability, and sustainability.
- Determine N, P, Cu leaching potential to identify the media components that minimize leaching potential, provide adequate hydraulic conductivity, and support growth of plant life.
- Assess the concentration of N, P, Cu and other pollutants in the stormwater effluent by combining different media blends in various ratios in a column design and rinsing them with deionized water

Study Methodology:

Laboratory testing	**Media components for the blends**	● Bulk aggregates: Volcanic and washed sand ● Bulk organic: iron coated wood chips and coconut coir pith ● Mineral additives: diatomaceous earth and activated alumina ● Organic additives: 1230W GAC, high carbon wood ash, and activated bone char	
	Media	Composed media blends shown in Table below	
	Flushing experiments	Goal	To evaluate pollutant leaching potential from the media
		Method and sampling	● Media packed into columns ● Media flushed 19 times with deionized water over a one month period (excluding weekends). ● Sampling done after 1st, 6th, 12th, and 19th flushing events. Volume of water required for flushing equivalent to one water year in the Seattle area with a bioretention area of 6.7% of the total contributing area.
		Results	● Initial flushing results showed some concentrations of total phosphorus, ortho-P, and dissolved Cu in the effluent, but continued to decrease over time. Blend using compost with other media had the highest amount of phosphorus in the effluent that subsequently decreased over time. ● Media using GAC and high carbon wood ash had the least amount of leaching.
	Dosing experiments	Goal	To evaluate potential of the media blends to capture pollutants in stormwater

		Method	● Columns dosed with natural stormwater or chemical augmented stormwater five times during the study period. Volume of water required for dosing was equivalent to 26% of a water year in the Seattle area with a bioretention surface area 6.7% of the total contributing area.
		Results	● Media blend consisting of compost resulted in high nitrate and phosphorus concentrations in the effluent. ● Media blends with GAC and high carbon wood ash captured most of the pollutants (TSS, ortho-P, and nitrate-nitrite).
	Conclusion	● Compost based media blends are not suitable for stormwater treatment as they have potential leaching of phosphorus, nitrate, and dissolved Cu and also have reduced contaminant capture as compared to non-compost blends ● Media blends consisting of coco coir pith, GAC, and high carbon wood ash performed the best in reduced contaminant leaching and increased capture. ● Appropriate blends are a 70% sand, 20% coconut coir, and 10% fly ash. ● Water retention and low organic matter composition was observed in all blends, but no significant plant growth performance pattern was seen.	



Media Treatment Name[a]	Bulk Aggregate	Bulk Organic	Mineral Additive	Organic Additive
60sand/40comp[b]	60% sand	40% compost[d]	NA	NA
70vs//20fe/10de	70% volcanic sand	20% iron-coated wood chips	10% diatomaceous earth	NA
70vs/20fe/10ash	70% volcanic sand	20% iron-coated wood chips	NA	10% high carbon wood ash
70vs/20cp/10de	70% volcanic sand	20% coconut coir pith	10% diatomaceous earth	NA
70vs/20cp/10gac	70% volcanic sand	20% coconut coir pith	NA	10% granulated activated charcoal[f]
70ws/20cp/10ash	70% washed sand	20% coconut coir pith	NA	10% high carbon wood ash
70vs/20cp/10ash	70% volcanic sand	20% coconut coir pith	NA	10% high carbon wood ash
90vs/10comp/p-layer[c]	90% volcanic sand	10% compost[e]	see footnote "c"	see footnote "c"

[a] Naming conventions for media treatments used throughout this document.

[b] Media treatment used default BSM specifications from the 2012 Western Washington Stormwater Management Manual (Ecology 2014) to serve as a control.

[c] Media treatment included a polishing layer consisting of volcanic sand, activated alumina, and bone char.

[d] Cedar Grove compost

[e] Land Recovery Incorporated Compost

[f] 1230AW (acid wash) coconut granular activated charcoal

ash: high-carbon fly ash
cp: coconut coir pith
de: diatomaceous earth
fe: iron-coated wood chips
gac: granular activated charcoal
vs: volcanic sand
ws: washed sand
p-layer: polishing layer
NA: not applicable

7. Biofiltration System Feasibility Study in the Port of Tacoma

Stormwater runoff in the Port of Tacoma in Washington, DC, has a very high pollutant load due to debarking activities. They sought a cost effective solution for the log dock or faced a closure. With a focus on environmental stewardship and sustainability, the Port of Tacoma aimed to identify the key treatment processes that would ensure efficient stormwater treatment. In collaboration with Kennedy Jenks, a four-stage biofiltration system was chosen for installation at the yard.

Study Objectives

- Identify a treatment capacity that can achieve the Industrial Stormwater general permit (ISGP) along with removal of several contaminants, meeting land use and area requirements, through Low Impact Development (LID) and other environmental and cost benefits
- Implement the stormwater treatment system within a set time frame

Study Methodology

The study methodology included a pilot study, followed by some bench scale column tests, and additional pilot studies.

Pilot Testing at the yard (Fitchthorn et al., 2014)

Pilot Study	Goal	To evaluate the effluent runoff quality after a stormwater treatment through two adsorptive media: ● Non proprietary biofiltration soil mix (BSM) ● Proprietary high flow media (PHFM)
Bench scale column tests	Goal	To evaluate effectiveness of media to treat stormwater runoff from the West Hylebos Log Yard
Additional pilot tests	Goal	To evaluate hydraulic performance of the system to assure that the system performs well and the water continues to move quickly through the system to maintain footprint.

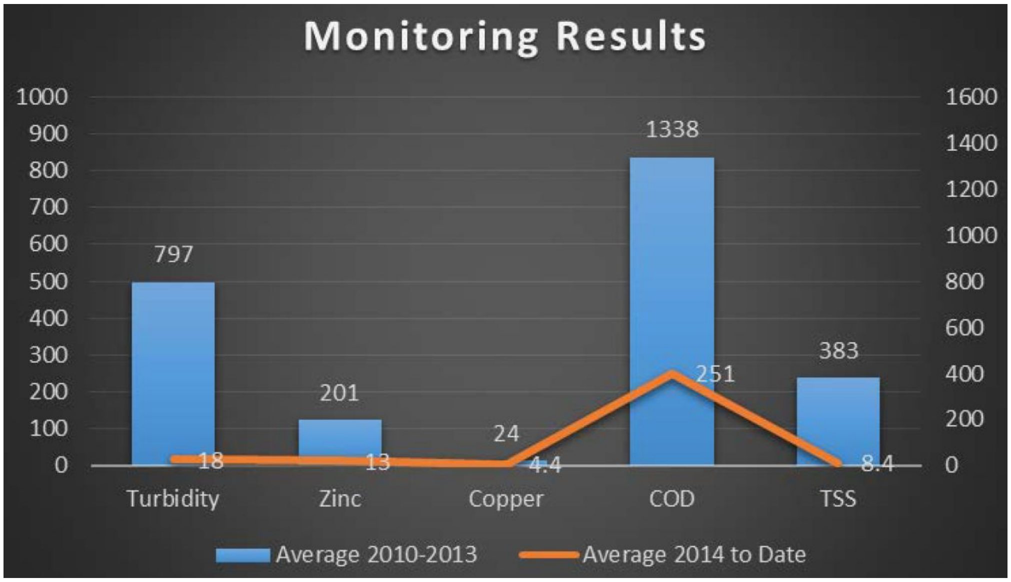
Installation

The four stage biofiltration system, with an area of 2500 m2 had the following layers:

Topmost (1st) layer	Amended sand with compost + vegetation	Helps to filter and biologically remove remaining pollutants. Plants were selected to ensure highest pollutant uptake ability
2nd layer	Amended sand with biochar	Helps to filter and chemically remove fine solids, metals, and organic contaminants (COD).
3rd layer	Pea gravel	Helps retain treatment media, and filters gross and settleable solids
Bottom (4th) layer	Drain rock	To drain the 'cleaner' stormwater with minimal pollutants
Underdrain pipes below the drain rocks		Collects filtered stormwater

Results:

- Overall, contaminant removal was obtained with reductions of 92% zinc concentration, 81.3% copper concentration, 94% reduction in turbidity, and 85% reduction in total suspended solids.



Results pre and post treatment (Fitchthorn et al., 2014)

- For the Port of Tacoma, the initial capital costs were reported to be about $1.8 million (USD), and about $0.95 million USD over a 39 year life cycle. Overall, the total cost of the system (capital, operation, maintenance) was around $4.43 million USD.

8. Application of Black Carbons (Activated Carbon and Biochar) for Trace organic carbon removal

Ulrich et al (2015) conducted a feasibility study on the effectiveness of black carbons (activated carbon and biochar) for enhanced removal of trace organic carbons (TrOC), that are classified under chemicals of emerging concern (CECs), from stormwater runoff.

Study Objectives

- To enable prediction of TrOC breakthrough times for black carbon amended stormwater infiltration basins through using forward-prediction models verified with laboratory tests.

Study Methodology

Laboratory tests	Black Carbons (BCs)	18 BCs were screened for their properties and production details. Out of these, after the batch experiments, 2 commercially available biochars and activated carbons were selected for further verification through column tests. ● 2 wood based pyrolysis biochars from Biochar Now - BN biochar 108 m2/g SA) and a gasification biochar from Mountain Crest Gardens (MCG - biochar, 318 108 m2/g SA) (wood based biochars chosen because of their ease of availability) ● AC from Calgon Filtersorb 300 (F300 - AC, 883 108 m2/g SA) (also used as standard/control)	
	Stormwater	Synthetic stormwater was prepared for evaluation containing TOrCs included 2,4-diphenoxyacetic acid (2,4-D), benzotriazole, atrazine, diuron, oryzalin, tris(3-chloro-2-propyl)phosphate (TCPP), prometon, and fipronil, based on occurrence in urban stormwater, recalcitrance, and mobility.	
	Batch experiments	Goal	To identify commercially available biochars that represent a realistic range of performance in model verification, in an effort to provide a wider range of biochars that can be used for stormwater management.
		Monitoring	Kinetics and capacity of the BCs and the TrOC concentration in the effluent was monitored.
		Results	18 BCs were evaluated, out of which 8 biochars were narrowed down and tested again with synthetic stormwater containing Suwannee River NOM and sodium azide. ● Out of these 8, 2 media were chosen : BN-Biochar and MCG-biochar were chosen for the column experiments. ● TrOC absorption in commercially available biochars can be maintained with the presence of DOC.
		Conclusion	Selection of the appropriate BCs depends on their success in batch tests.
	Column experiments	Goal	To verify forward prediction models describing sorption on filter media

		Method	Sand + biochar layer of height 12 cm packed in the column. Synthetic stormwater used to assess performance of the media layer.
		Results	Experimental results were used to simulate models that can predict these results: ● MCG - biochar retained more TrOC effectively as compared to BN - biochar; while the performance was opposite for benzotriazole retention. ● Biochar and AC can both prevent atrazine breakthrough for 5 years, and AC can prevent breakthrough for multiple decades, depending on the flow rate ● For F300-AC, a maximum breakthrough time of 54 years at a dose of 12.3 wt % AC was estimated for case 1, and a maximum infiltration rate of 4.3 in./h at a dose of 4.9 wt % was estimated for case 2. ● For MCG-biochar, a maximum breakthrough time of 5.8 years at a dose of 4.5 wt % was estimated for case 1, and a maximum infiltration rate of 3.0 in./h at a dose of 2.9 wt % was estimated for case 2.

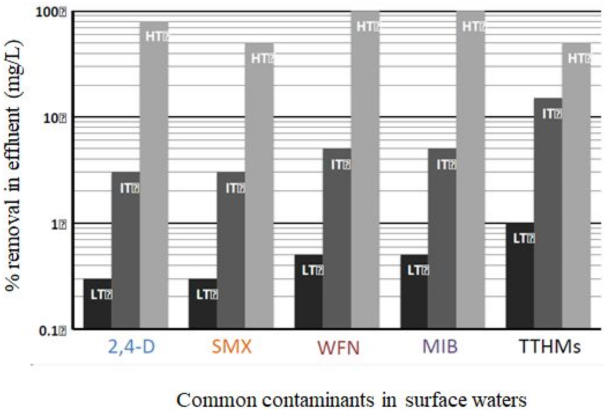
Conclusion

- Based on model data, For an infiltration basin of 100m2 at 12.3 wt % AC, about 11.8 tonnes of AC will be required (AC cost $1500/ton). Biochar on the other hand, is significantly less expensive (break-even costs of $250/tonne).

Biochar has added benefits of carbon sequestration and superior metal retention. Based on model results, considering the infiltration basin has enough space to drain at 1 in/hour, the longer hydraulic retention time of the biochar amended media will allow for more biodegradation of these TrOCs and have greater removal.

9. Comparison Biochar with AC for trace organic contaminant removal

Kearns (2018) reported on the feasibility of biochar to remove trace organic contaminants (CECs) from surface waters (rivers or lakes) for use in household drinking water purposes. The main CECs considered for the study were 2-4-D (2,4-Dichlorophenoxyacetic acid), SMX (sulfamethoxazole), WFN (Warfarin), MIB (2-methylisoborneol), and TTHM (trihalomethane).



Removal of trace organic contaminants by AC and biochar (Kearns (2018))

Biochar type

- Kearns used a longan wood biochar (pyrolysed at 650℃ (IT) and 900℃ (HT)) and activated carbon (LT, pyrolysed at 350℃) of size 500µm.

Conclusion

Kearns concluded that high temperature pyrolyzed biochars were capable of absorbing 50-100% of toxic organic chemical contaminants as compared to commercial ACs, making it a viable and cost effective option for use in local water treatment and eco-sanitation.

10. Application of biochar enhanced wetland for removal of contaminants in agricultural wastewater

Gugolz and Nzengung (2017) studied the performance of a low cost and maintenance biochar amended wetland for removal of contaminants like nitrogen, phosphorus, heavy metals, and CECs from agricultural (swine) wastewater. Biochar, along with plants, in the constructed wetland (CTW) systems can combine physical, biochemical, and uptake of nutrients, metals, and organics and are adaptive to environmental changes. These wetlands can be operated semi-passively, and also offer opportunities for carbon sequestration.

Study Objective

- To evaluate the performance of a biochar amended wetland system for nutrient removal.

Study Methodology

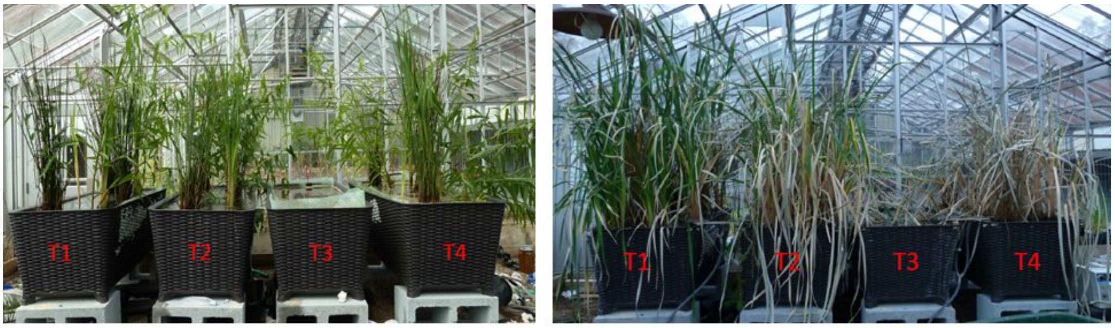
Bench Scale tests	**Biochar**	From Biochar Now, soft wood biochar produced by pyrolysis at 550℃.	
	Results	Ammonia loading on biochar was expected to be 280mg/kg of biochar, and about 98% of it was desorped into distilled water on rinsing. Rinsing was done to remove any clogged particles or other organic particles from media pores. Some of the ammonia is bioavailable for plants to use.	
Pilot scale tests	**Apparatus**	Four types of biochar amended CTW: ● T1: Plants + full biochar in CTW ● T2: Plants + half biochar in CTW ● T3: Full biochar in CTW ● T4: Plants in CTW	
	1st test (Fall Test)	Goal	To conduct a greenhouse experiment using biochar and plants in the CTW planters for nutrient removal from agricultural wastewater
		Source water	Twice diluted swine wastewater
		Methodology	Flow rate was set at 2L/hr and a residence time of 33.5 hours in the planters.
	2nd test (Spring test)	Source water	10 times diluted swine water (Test in April) and 5 times diluted swine water (test in May-June)
		Methodology	Flow rate was set at 1L/hr and a residence time of 67 hours in the planters.
	Results	● Total suspended solids removal: The combination of plants and biochar (T1 and T2) had similar removal of total solids, with 56% and 16% more removal than T3	

		and T4 respectively ● COD removal: T1 and T2 had similar COD removals, but 29% and 12% more than T3 and T4 respectively ● Ammonia removal: T1 removed 5%, 50%, and 23% more ammonia than T2, T3, and T4 respectively ● Phosphate removal: T1 and T2 had similar phosphate removals, and 42% and 13% more removal than T3 and T4 respectively ● Potassium removal: T1 and T2 had similar phosphate removals, and 109% and 33% more removal than T3 and T4 respectively

Conclusion

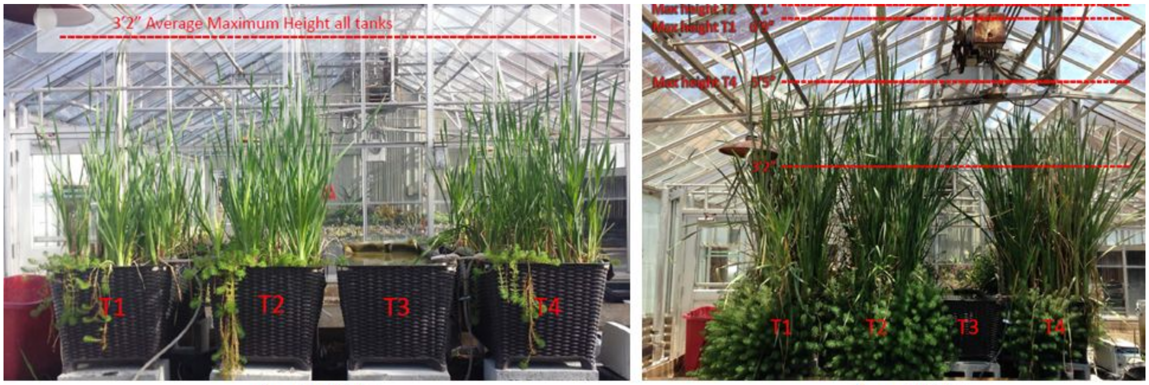
- The combination of biochar and plants increased nutrient removal from agricultural wastewater, with a much better performance than biochar and plants alone.

Biochar + Plant > Plant alone > Biochar alone



August 2015 *November 2015*

1st test - Fall 2015



April 2016 *June 2016*

2nd test - Spring 2016

Images of the study from Gugolz and Nzengung (2017)

11. Application of biochar for removal of emerging contaminants in aqueous solutions

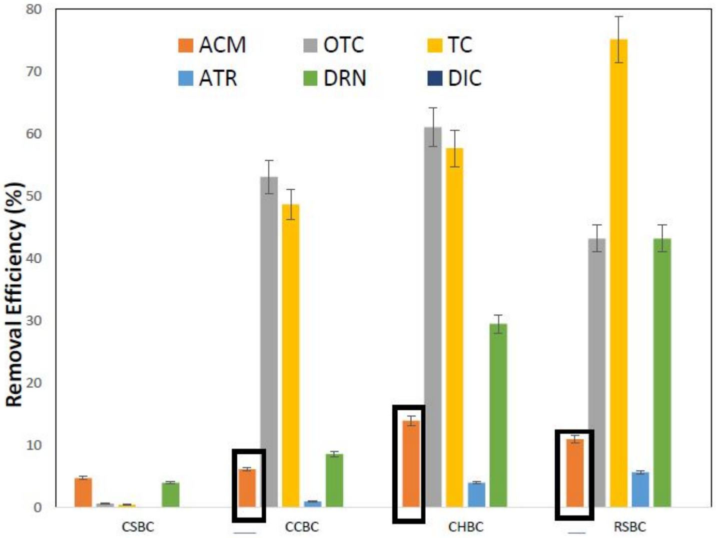
Johnson et al (2019) evaluated the adsorption dynamics of emerging contaminants (pharmaceuticals and pesticides) in aqueous solutions onto biochar derived from different feedstocks.

Study Objective

- To evaluate the performance of CEC removal from wastewater by a locally produced biochar from different feedstocks.

Study Methodology

Biochar	4 types of biochar: ● Coconut shell biochar (CSBC) ● Corn cob (CCBC) ● Coconut husk (CHBC) ● Rice straw (RSBC)	
Target contaminants	● **Pharmaceuticals:** Acetaminophen (ACM), Tetracycline (TC), Oxytetracycline (OTC), Diclofenac (DIC) ● **Pesticides**: Atrazine (ATR), Diuron (DRN)	
Batch adsorption study	Goal	To investigate adsorption dynamics of selected micropollutants on biochars derived from the four feedstocks
	Methodology	Adsorbent dosage set at 5g/L
	Results	Variable removals by the different biochars; ● CSBC had the lowest removal for all the contaminants ● TC removal was highest with RSBC, followed by CHBC and CCBC, and negligible removal with CSBC ● OTC removal was highest in CHBC followed by CCBC and RSBC ● DRN removal was highest for RSBC, followed by CHBC and CCBC ● ATR removal was relatively low in all biochars compared to other contaminants Due to higher removal of contaminants compared to other biochars, CHBC was chosen for a small scale column study.
Small scale column study	Goal	To determine the stability of CHBC as a medium for removing microcontaminants in pond water
	Biochar media	42.3g CHBC-sand mix (10% w/w) media and 77.7 g of fine sand (control media)
	Water sample	Pond water spiked with target contaminants
	Methodology	Media bed of 20 cm in a column of diameter 1.8 cm



Removal of CECs by the four biochars in batch adsorption study (Johnson et al., 2019)

Conclusion

- All blends of biochar showed variable removal efficiencies. Adsorption of pollutant over the biochar media depends on contact time and sorbate type. Removal efficiencies can be increased with increase in sorbate dosage and biochar modification.
- No conclusion on bio-activity of the biochars.

12. Application of wood biochar for contaminant uptake

Flashinski (2018) studied the application of wood biochar for contaminant uptake from reclaimed water by corn plants. Contaminants of emerging concern (CECs) like pharmaceuticals and personal care products (PPCPs) are often found in reclaimed water, but there is a lot of potential in reusing reclaimed water to combat irrigation water shortages.

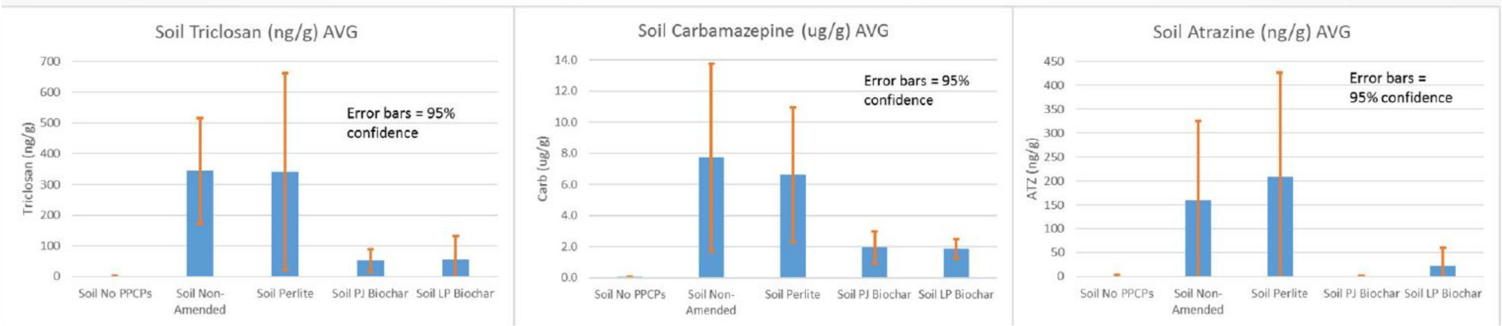
Study Objective

- To evaluate the performance of wood biochars for plant growth and PPCP availability.
- To determine the amount of PPCPs sorped on the biochar
- To evaluate if the biochars allow for bioavailability

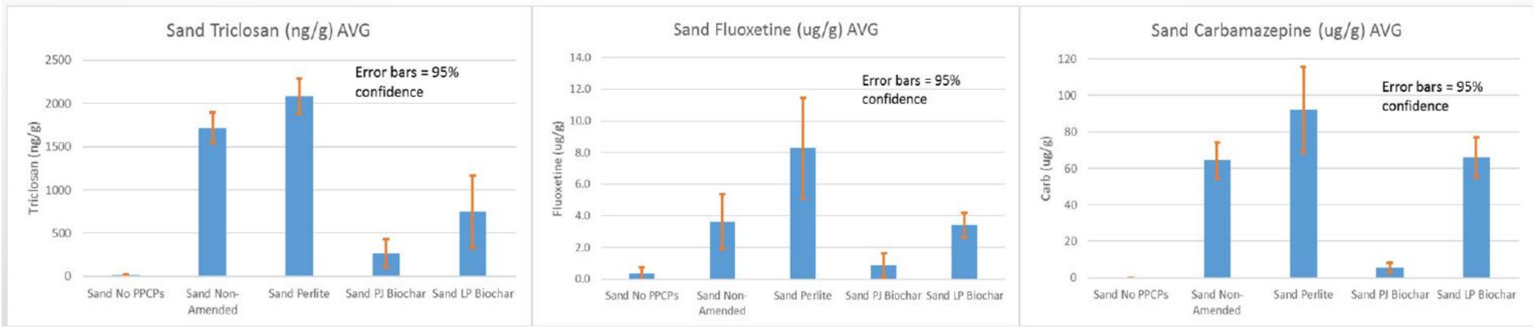
Study Methodology

Experimental Study	Media	Biochar (5% by mass) mixed with soil (Clay loam, organic matter 2.7%, pH 7.7) and sand mixtures Biochars from invasive or infested tree species in Intermountain west: ● pinyon juniper biochar (62.4% carbon) ● odgepole pine biochar (62.3% carbon)
	Target contaminants	Sulfamethoxazole, Ccarbamazepine, Fluoxetine HCl, Atrazine, Triclosan

	Water sample	Reclaimed water from Hyrum wastewater treatment plant with 1mg/L PPCP spike
	Methodology	Corn plants (Corn seeds from Sygenta 8590GT 2006) were grown for 28 days in soil (clay loam, organic matter 2.7%, pH 7.7 – slightly alkaline) or sand mixtures within a PVC column. Sorption coefficients were estimated using column sorption tests.
Column Study	Media	4 pairs of media were tested for comparison ● Soil and sand ● Non-amended media and biochar media ● Non-spiked and spiked irrigation water ● 4 columns with and without corn used for evaporation



Soil uptake of contaminants (Johnson, 2018)



Sand uptake of contaminants (Johnson, 2018)

Conclusion

- Biochar had no extraordinary impact on plant growth, with the pinyon juniper biochar allowing for the greatest growth in soil and sand
- Reduced uptake of contaminants by plants in soils amended with biochar, with better performance by the pinyon juniper biochar
- Except atrazine, overall concentration of contaminant in leaves were seen to follow the following trend:
  - Sand > Soil > Soil + biochar (It may be inferred that biochar amended soil media can result in a greater accumulation of contaminants within the media, reducing contaminant uptake in a plant. Due to this, there is a lower mobilization of the contaminant from the media to the plant through the roots).
  - carbamazepine > fluoxetine > triclosan > atrazine > sulfamethoxazole

13. Application of biochar for sorption of agrichemicals

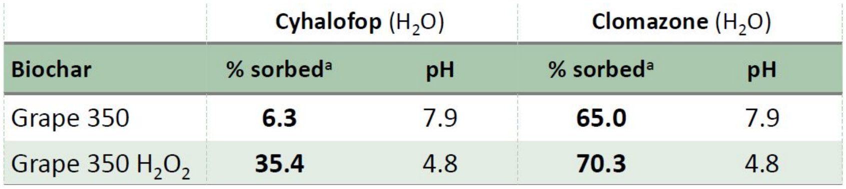
Hall et al (2016) studied the interactions between biochar properties and agricultural pesticides (categorized under CECs) to understand the sorption mechanisms and best identify how biochars can be designed to target select pesticides.

Study Objectives

- To identify methods that can ‘activate’ biochars to create normalized sorbent materials - leading to production of activated biochars
- To understand how surface chemistry of biochars help in sorbing select contaminants

Study Methodology

Biochar types	3 types of biochar from grapewood feedstock were prepared: ● Pyrolysed at 350℃ ● Pyrolysed at 500℃ ● Pyrolysed at 900℃
Activating materials	H2O2, CO2, HCl, H2SO4, H3PO4, HNO3
Target contaminants	Cyhalofop and Clomazone
Results	● Clomazone was equally sorped on all the biochars (slightly greater sorption at 350℃ than 500℃) as compared to cyhalofop ● Activation visibly changed surface chemistry of the biochars; and enhanced pesticide sorption observed.



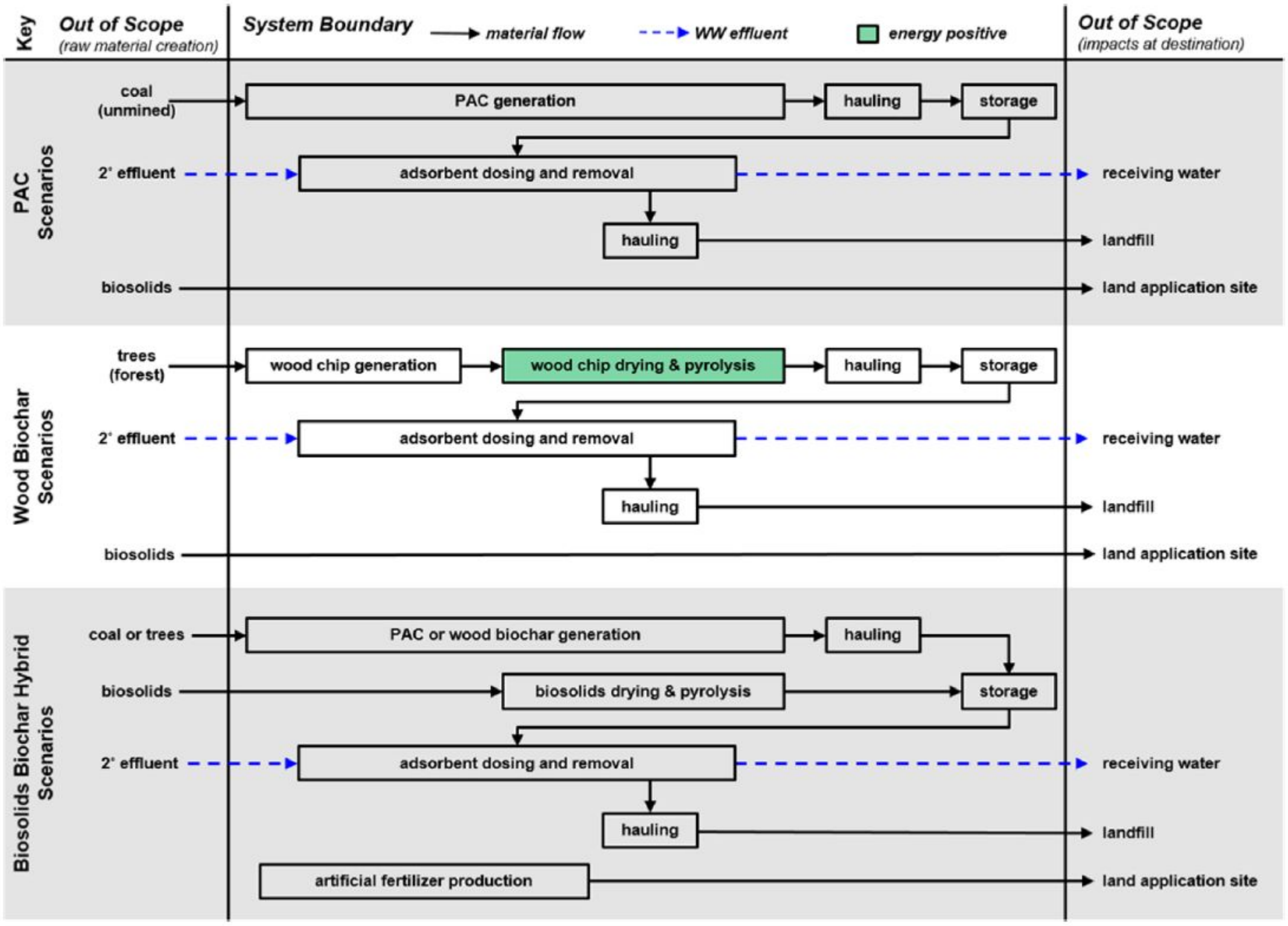
	Cyhalofop (H_2O)		**Clomazone** (H_2O)	
Biochar	**% sorbed**[a]	**pH**	**% sorbed**[a]	**pH**
Grape 350	**6.3**	7.9	**65.0**	7.9
Grape 350 H_2O_2	**35.4**	4.8	**70.3**	4.8

Conclusion

Designer biochars can be made with activation for obtaining desired sorption properties and intended uses.

14. Life cycle environmental impact assessment between AC and biochar

Thompson et al. (2016) compared 10 environmental impacts between AC and biochar, to offer some insight into the life cycle of both these products.



Process flow diagram used for the Study (Thompson et al., 2016)

Study Objectives

- To quantify relevant environmental impacts of using biochar adsorbents for tertiary wastewater treatment made from wood and biosolids as compared to powdered activated carbon (PAC).

Study Methodology

Methodology		Comparative adsorbent methodology following ISO 14040 framework
Study	Functional unit	75% removal of sulfamethoxazole (SMX) from 47 300 m3/day (12.5 mgd) of secondary wastewater effluent over 40 years. SMX was chosen as the CEC for the study as: ● It is commonly found in wastewater and some surface waters

		● 75% removal of SMX is obtained at any wastewater treatment process ● Regulations surrounding CECs are exploring to consider 80% removals and SMX has a lower tendency of getting absorbed compared to other CECs. So, 75% removal of SMX would imply greater removal of other micropollutants. Typical SMX concentrations in wastewater effluent are ≤0.178 µg/L in China,38 ≤ 2.00 µg/L in Germany,39 and ≤3.25 µg/L in the U.S.
	Adsorbent dosage	Compiled from other bench scale work, the amount of dosage required to achieve 75% SMX uptake from wastewater effluent over a 60 min contact time was taken into consideration. Based on this, the different adsorbent scenarios were defined: ● Dose for commercial bituminous coal-based PAC = 70 mg/L; low capacity (600 mg/L) and moderate capacity (150 mg/L) ● Low capacity wood biochar from pine wood chips pyrolysed at 400 - 1200℃ ● Moderate capacity wood biochar from pine wood pellets pyrolyzed at 850℃ ● Biosolids capacity was calculated from available data
	Adsorbent scenarios	6 adsorbent scenarios were considered: ● Low-impact PAC ● High-impact PAC ● Moderate capacity wood biochar ● Low capacity wood biochar ● Moderate capacity biosolids biochar + low-impact PAC ● Moderate capacity biosolids biochar + moderate capacity wood biochar Only the biosolids biochar has supplements because the study identified that on its own, the biosolids biochar would not be able to meet the required removal % as stated in the study.
10 Tools for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) from the EPA		The 10 TRACI midpoint impact categories are: ● ozone depletion (kg CFC-11 equiv), ● global warming (kg CO2 equiv), ● smog (kg O3 equiv), ● acidification (kg SO2 equiv), ● eutrophication (kg N equivalent), ● carcinogenics (comparative toxic units, CTU), ● non carcinogenics (CTU), ● Respiratory effects (kg PM2.5 equiv), ● ecotoxicity (CTU), ● fossil fuel depletion (MJ surplus).
PAC scenarios		Life cycle impacts of PAC were estimated for generation, hauling, and storage of PAC. Emissions of PAC generation from coal were estimated using Agri-footprint.
Wood biochar scenarios		Life cycle impacts of wood based biochar (from wood chips) were estimated for generation, hauling, and storage of biochar. Direct gas emissions of treated pyrolysis gas were estimated by modelling and measured data for wood biochar pyrolysis.

		Opportunities for offsetting some energy usage exist through energy recovery from the pyrolysis gas.
Biosolids biochar scenarios		Life cycle impacts of biosolids biochar were estimated for the generation, hauling, and storage of biosolids biochar and any supplemental adsorbent; the removal and landfilling of spent adsorbent; and fertilizer production due to biosolids diversion from land application. Direct pyrolysis emissions were based on a full-scale biosolids pyrolysis facility's emissions of treated and combusted pyrolysis gas.
Results	Wood biochar vs PAC	**Moderate capacity wood biochar vs low-impact PAC:** Production and use of moderate capacity wood biochar for SMX removal results in environmental impacts that are higher than low-impact PAC but lower than high-impact PAC in two categories (eutrophication, carcinogenics); environmental impacts that are lower than low-impact PAC in four categories (ecotoxicity, acidification, ozone depletion, fossil fuel depletion); and environmental net benefits in four categories (smog, global warming, respiratory effects, and non carcinogenics) that were not realized with low-impact PAC. **Low capacity wood biochar vs PAC:** Low capacity wood biochar had larger environmental impacts than both PAC scenarios in five categories (eutrophication, carcinogenicity, ecotoxicity, acidification, ozone depletion) and lower impacts in the other half of the categories (fossil fuel depletion, smog, global warming, respiratory effects, and non carcinogenics). Benefits were seen in global warming, respiratory effects, and non carcinogenics.

More case studies on the application of AC and biochar on field or in pilot scale studies are available in the US biochar initiative's online platform. The International Stormwater BMP database also contains a database of over 700 BMP studies, performance analysis results, tools for use in BMP performance studies, monitoring guidance and other study-related publications.

CONCLUSION

SUMMARY

From the literature review and case studies compiled on the application of activated carbon (AC) and biochar in stormwater management, the key conclusions from the review have been discussed.

Urban stormwater is a complex mixture of a variety of pollutants categorized into suspended solids, metals, nutrients, organics, and most recently, contaminants of emerging concern (CECs). The pollutant load and concentration in stormwater runoff differ greatly depending on the storm event (Hvitved-Jacobsen et al., 2010). Stormwater management systems aim to achieve not only the pollutant removal but also manage the runoff volume of extreme storm events. Low impact development (LID) stormwater management systems like raingardens, bioswales, retention ponds, etc. are favoured in urban areas; with advantages of increased stormwater infiltration and decreasing surface runoff through traditional media like sand, soil, or compost with plants growing over the media (Hunt et al., 2010).

Some research shows that although media like mulch and compost can remove heavy metals and sediments from stormwater runoff, as more CECs start appearing in stormwater runoff, the viability of the traditional stormwater management systems consisting of only sand or soil media has become a concern. Research into the use of AC and biochar for stormwater management shows that these media are effective in removal of several contaminants within the different pollutant groups. Depending on the type of pollutant, AC and biochar offer different removal efficiencies. For metals, AC, in general, is more effective in removing Pb, Cu, Zn, Ni and Cd, however, biochar offers similar to greater removal of Cd, Cr, and Hg (II) (Mohanty et al., 2018). For nutrients, AC is not as effective as biochar due to the difficulties in development of a microbial ecosystem over the AC surface area (Amini et al., 2018). For CECs, the pollutant removal varies with the pollutant type; with AC's offering higher removal of polychlorinated compounds and biochar offering higher removal of pyrene, trace organics, and opportunities for bioaccumulation (Mohanty et al., 2018). Overall, the removal efficiencies differ greatly based on the type of AC and biochar, i.e the feedstock raw material, production processes, and the design of the stormwater management system.

Within a LID system, AC and biochar amended soil or sand can aid the growth of plants while offering pollutant removal. Plants inherently offer opportunities for pollutant removal through nutrient uptake and synthesizing carbon for growth. They can also improve soil permeability through a phenomenon called 'root turnover' that can prevent clogging of sand, soil or the media. AC and biochar media can improve plant growth in the stormwater management LID systems and soil properties through enhanced water retention and slow release of nutrients (Mohanty et al., 2018). Both AC and biochar allow for some bioaccumulation of pollutants within their structure; however, there may be some concerns of increased soil toxicity over time and uptake by plants. If mobilized within the plant, as seasonal changes occur and leaves fall and decay, there is a possibility that the organics containing the contaminant may again add to the stormwater runoff. Leaching of the pollutants from the media is also a concern over time, as some phosphorus leaching has been observed in compost media (Sigua et al., 2016).

'Designer' media blend of AC and biochar can also be made to target specific pollutants that may be present in the proposed site. The Port of Tacoma, due to its location, faced challenges of a high stormwater runoff volume and pollutant load (heavy metals and sediment); their designer stormwater management system using biochar amended soil media aimed to achieve, in particular, only metal and suspended solids removal for the site

(Fitchthorn et al., 2014). Through chemical and physical processes, properties of the media itself can be changed or 'activated' to obtain the desired properties to remove target contaminants. Hall et al., (2016) studied activated biochars for removal of pesticides from agricultural wastewater and observed that activation improved pesticide removal in the activated biochar. Additionally, if the media gets clogged with pollutants, the removal efficiencies are lowered, and require replacement or cleaning.

Raw materials for AC and biochar require energy associated production processes, which add to the cost of the stormwater management system. Comparatively, AC requires a more energy-intensive production method as compared to biochar. Lower energy consumption and higher production yield make biochar a more attractive option for a large scale application (Thompson et al., 2016). Additionally, with both AC and biochar, there are opportunities for reuse of agricultural wastes, energy recovery, and carbon sequestration in the amended soil (Elkhakufa et al., 2019).

It can be concluded from the review conducted that both AC and biochar can be used for stormwater management in urban communities. However, choosing the most appropriate media would depend on the physical and chemical properties of the media blend and the target pollutant in the proposed site. The media blend directly impacts the removal efficiency and the overall life cycle of the stormwater management system. Beyond implementation, operations and maintenance costs are also driven by the media blend's properties.

RESEARCH GAPS

Biobased carbons include biochar, charcoal, and activated carbon that are derived from biomass (Chargrow, 2018). Also, charcoal is often used to describe other carbon products, and 'activated charcoal' is typically used interchangeably with 'activated carbon'. Sometimes, the definition of biochar may describe it as 'charcoal'. Categorization of biochar is also difficult, as it may require to be 'activated' for property modification, and is known as activated biochar in industry. Other biobased carbons used in remediation or filtration are termed as biobased carbon or activated carbon. Hence, there is currently some confusion on the definition of these products, and although is not a research gap, it complicates the review process.

Some significant research gaps identified during the review of using AC and biochar in stormwater management have been discussed in this section.

Current lack of pollutant characterization and relevant guidelines and regulations

While the characterization of metals and nutrients is fairly simple, characterizing CECs is quite complex as many compounds grouped under CECs are not yet measurable and their impact on human health is unknown. Climate and weather conditions, land-use, and surrounding environmental conditions impact the presence of the CECs, which vary on a regional basis. Currently most stormwater guidelines are driven by two main factors - volumetric reduction of stormwater runoff and sediment and nutrient control. Additionally, impact on aquatic life is currently a measurable factor driving guidelines. To inform relevant stormwater regulations, more research into CECs and their quantification is the need of the hour. Currently, stormwater quality guidelines adhere to EPA's water quality criteria, maximum contaminant level for drinking water, ecological nutrient criteria, human health concentration for human consumption, and similar regulations. Standards to better improve the design and performance of bioretention systems have been developed by Chris Johnston and his partners with the National

Standard of Canada, namely the CSA W200-18 Design of Bioretention Systems and CSA W201-18 Construction of Bioretention Systems.

Most studies are lab-scale

The current state of research on using activated carbon and biochar for stormwater treatment and management are either laboratory or bench-scale based, mostly using synthetic stormwater containing one or a couple of target contaminants. However, storm events are highly complex and intermittent with variable characteristics of intensity and duration, that in turn impact their pollutant load. Due to this, the impact of complexities of stormwater like flow changes, changing weather, pollutant concentrations etc cannot be fully understood on such a smaller scale and results from the lab tests cannot be expected to be the same on the field.

Additionally, most lab scale studies investigate removal of only a few pollutants in a less complicated matrix compared to stormwater. Several pollutants may interact with each other and competition may occur, but it is not yet known how the biochar or activated carbon media may remove contaminants under such a mixture of compounds. Further, there is a large inconsistency in the media blends used in the studies, with no particular justification for the media blends chosen in the studies for stormwater treatment.

Results are highly site-specific

Most of the lab scale as well as on field studies reported in literature have been on a smaller scale and for very specific reasons like control of contaminants in a log yard, mine site reclamation, or growth of plants in a contaminated site. All of these studies used different biochars and activated carbons that were commercially available or were by-products of a local industry.

Several studies also speak to the fact that inherent stormwater characterization and soil studies of the site where a stormwater LID system is being proposed is important to identify the type of product best suited for the area. The LID life-span is also quite site-specific and design-specific, and is impacted by the rainfall intensity, catchment area, and other land uses.

Currently, results of the studies cannot be universally applied for various applications, and hence, there is no specific activated carbon or biochar product available that can be applied to all sites.

Discrepancy in reported results on impact of other media within a blend

There are some knowledge gaps on if and how the presence of other media like compost may impact the biofiltration LID systems. Some studies reported increased nutrient leaching in the stormwater runoff due to the presence of compost. Others have reported no significant changes in leaching of nitrate, phosphorus, and DOC. There is need for further research and studies into these inconsistent results, particularly over the long term when bioaccumulation of pollutants occur.

Leaching of contaminants is a concern

Several studies have reported leaching of contaminants into infiltrating water from the AC or biochar media. Particularly, as the media continues to remove contaminants from the runoff and accumulate within the media, there may be a concern if there is long term leaching of these contaminants or newer blends of compounds into the stormwater runoff or discharge. For this, pilot scale studies stretching for a couple of years may be necessary.

Impact of biological processes is not clearly known

The long term stability of the engineered media against the growth of microbes, organic clogging, etc. has not been explored in most of the lab-scale studies, mostly as the lab studies were over a short period of time or within one storm event season. The impact of changing flow conditions of storm events on biodegradation and release of organic contaminants is a knowledge gap that must be looked into.

Additionally, while studies have shown that biochar enhances plant growth in soils, it is not yet known how or what biochar properties benefit plant growth in bioretention systems. Hence, interactions between biochar, plants, and microbial communities with varying dry periods must be studied.

Product weathering and ageing is yet unknown

Presently, it is still unclear how the activated carbon or biochar layers ‘age’ or weather in actual field conditions, where there are impacts of environmental factors (weather) and presence of co-contaminants. Some studies also reported the physical erosion of biochar particles from the stormwater treatment systems, which is yet to be investigated. The life of the LID system depends on the adsorptive capacity of the media and ageing processes that are complex in nature. Artificial ageing processes in laboratories are not enough to predict their performance in the field.

There is no long term study on any implemented systems, particularly because the field of research on biochar’s application for stormwater treatment is relatively new.

Regeneration of product is yet unknown

For a sustained viability of the stormwater management system over a long period of time, the media has to maintain hydraulic properties. However, challenges of solids clogging within the pores of the media remain, which can increase the overall operations and maintenance costs. Some pilot scale studies recommend rinsing the media over time to be able to reuse it for further uses after it gets clogged. Rinsing with deionized water may help in removing suspended solids from the media, but this is impractical for large scale stormwater management systems. For removing clogged organic contaminants, chemicals like sodium azide or highly concentrated brine might be required to regenerate the media, which brings in problems of disposal of leached contaminants.

Additionally, it is not yet known when the media may get saturated, and if there is a cost trade-off between media replacement and media regeneration. Further, protocols for ease of inspection, maintenance, and replacement would need to be incorporated in the best management practices associated with stormwater treatment and management.

Design of engineered treatment systems with activated carbon and biochar media must be studied

While studies on hydraulic conductivity and water retention have been conducted on the media, the results are associated with agricultural land, but no quantifications on sand or sandy soil which are commonly used in LID systems have been made. This gap must be considered to help design better engineered systems.

RECOMMENDATIONS

Based on the conclusions and research gaps identified, the following recommendations can be made for future work into the use of AC and biochar for stormwater management.

Opportunities for collaboration

Best stormwater management practices call for collaboration between practitioners to develop open source up-to-date manuals and guidelines based on research on stormwater management. Online platforms like the US biochar initiative and the international stormwater BMP database are a rich source of information for different types of research and BMP performance summaries.Peer to peer knowledge exchange must be encouraged between researchers across the field, and between stormwater designers and local decision makers.

Opportunities for establishing a sustainable circular economy

Anthropogenic activities like irrigation and other industrial sectors generate a large amount of wastes that contribute to stresses on our natural systems through impacts associated with both production and disposal. A sustainable waste management structure asks to utilize any waste as raw materials for production of new products like fuels or chemicals, thereby shifting the current linear model of most industries to a circular based economy. Value added products like biochar and AC from biomass and other waste materials can be produced using thermo-chemical processes (eg. pyrolysis).

Through the literature review, it is evident that both AC and biochar are effective adsorbent media for removal of contaminants from stormwater runoff. The raw materials or feedstock required for the production of the media can be sourced from local irrigation or industry. This would not only minimize waste going to landfill, but also reduce emissions from transport of materials. Use of these residues for AC or biochar production can help close the loop in agriculture and achieve circular economical benefits.

Decentralized gasification-based units for combined heat and power and AC or biochar pyrolysis can be an efficient way to meet energy demands by using local biomass, whilst avoiding transportation costs, creating business and employment, improving resource recovery and efficiency, closing nutrient loops, and providing synergistic opportunities for many sectors like agro-industry, bioenergy, and waste management sectors (Fytili and Zabaniotu, 2018).

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APPENDIX 1: Pollutant removal mechanisms

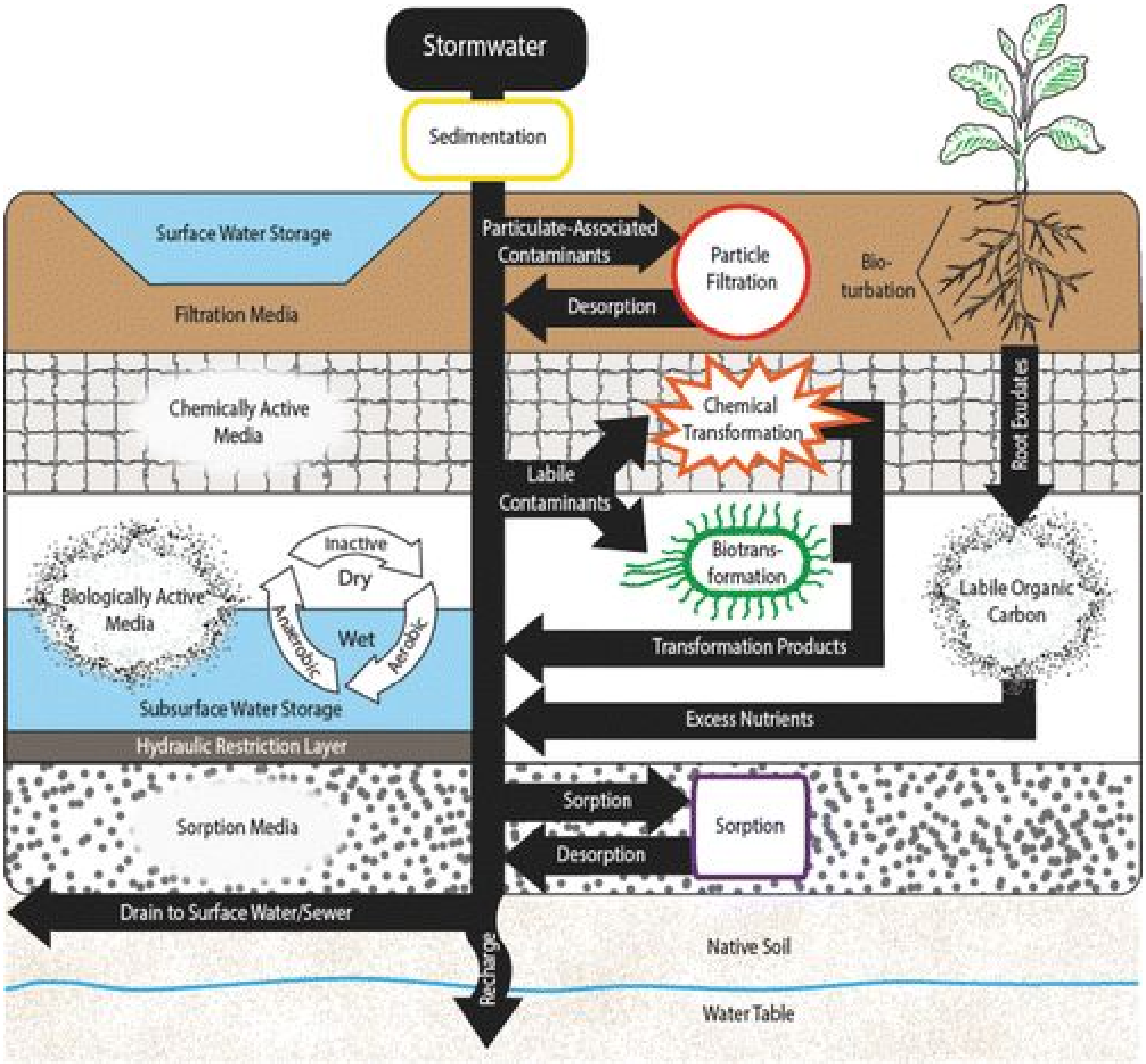
This section includes information on the infiltration mechanism of pollutants in a stormwater treatment system.

Grebel et al., (2013) defined that the three main mechanism of removing pollutants in a infiltration based stormwater system are:

- Filtration
- Sorption
- Transformation

The main factors that drive the choice of a media for enhanced contaminant removal are:

- Proper choice of infiltration media;
- Control of system hydraulics; and
- Control of redox conditions within the infiltration system.



Contaminant behaviour in a stormwater infiltration system (Grebel et al., 2013)

APPENDIX 2: Biochar production processes and formed product

This section shows that based on the type of production method used for biochar production, the end product may vary.

Thermochemical processes for biochar production	**Process description**	**Product formed**
Pyrolysis	Burning of the biomass under limited oxygen supply and high temperature of 300-800°C. ● Slow pyrolysis - long vapour residence (ime (> 1 h) and slow heating rate (5–7 °C/min) ● Fast pyrolysis - short residence time (> 10 s) at high heating rate (> 200 °C/min)	Slow pyrolysis - High yield of biochar Fast pyrolysis - Low yield of biochar
Gasification	Burning of biomass under higher temperature (> 700 °C) in O_2 or steam as oxidants.	Biochar is the solid co-product with syngas as the main product.
Hydrothermal carbonization	Less energy intensive (180–250 °C)	Hydrochar (biochar analogue)with low syngas production (1-5%).

Appendix 3: Commercial stormwater treatment systems

This section includes some commercial stormwater management systems currently available.

- **Stormwater management by Stormwater 360, New Zealand**

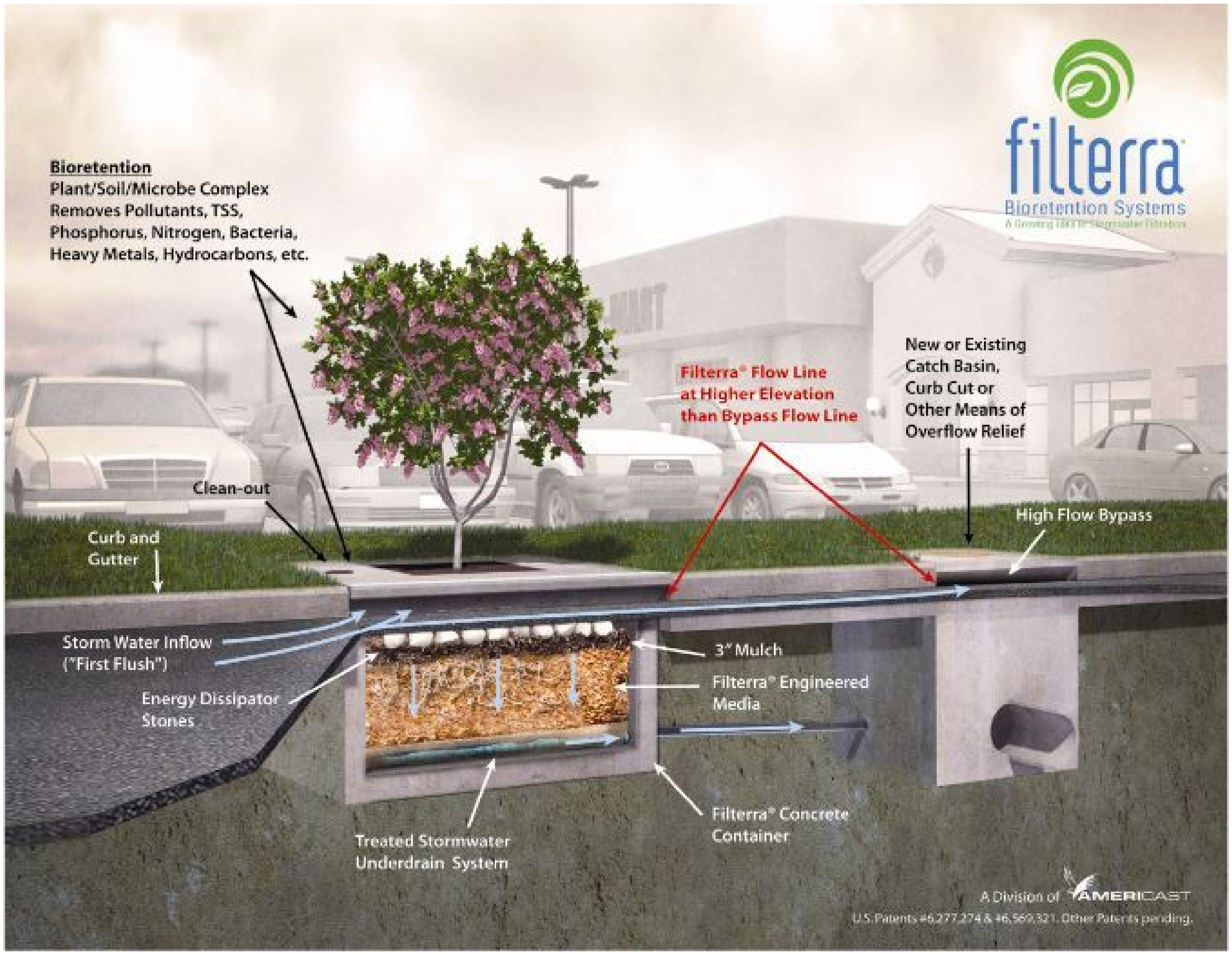
Stormwater360 are a company in New Zealand, with over 24 years of experience in stormwater management. They offer a wide range of different stormwater management systems for specific purposes. Some of them are:

Stormwater management products from Stormwater 360

Product	**Structure**	**Target pollutant and function**
StormFilter	A vault or manhole structure that houses rechargeable, media-filled filter cartridges	Total suspended solids, hydrocarbons, nutrients, soluble heavy metals, and other common pollutants.
Jellyfish Filter	Cartridge filters with gravity, flow rotation, and up-flow membrane filtration	Floatables, litter, oil, debris, TSS, silt-sized particles (as small as 2 microns), and a high percentage of particulate-bound pollutants; including phosphorus, nitrogen, metals and hydrocarbons.
Enviropod Filter	A catchpit insert, fitted with a re-usable, polyester filter bag, available with several mesh screen sizes and oil-absorbent media dependent on the pollution generated from each specific site.	Litter, suspended solids, and other gross pollutants
Littatrap	A catchpit insert, the water passes through the LittaTrap filter bag and litter, debris, and plastic larger than the holes in the filter bag (5mm) are captured and retained.	Plastic and rubbish
VortCapture	The system combines the proven sediment removal capability of hydrodynamic separation with superior litter and organic debris capture.	All particles greater than 5mm in size.
VortSentry HS	A hydrodynamic separator	Settleable solids and floating contaminants
Vortechs	Pollutant trap	Fine sediment, oil and grease and floating and sinking debris
Cascade separator	A hydrodynamic separator	Sediment and gross pollutants, hydrocarbons, litter and debris
Vortclarex	Oil and water separator	Oil and grease

Fox Valves	Diversion system	To Divert first flushes stormwater runoff
ESK	A coalescing separator	Oil and grease
ChamberMaxx	A corrugated, open-bottom plastic arch system	To detain or retain stormwater runoff

Other than these products, Stormwater360 has another product called the Filterra® Bioretention System that enables efficient natural flow of stormwater runoff to capture and remove pollutants. These bioretention systems can effectively remove TSS, phosphorus, nitrogen, metals, oil and grease. Filterra has a small footprint and engages plant species for stormwater management and aesthetic purposes. According to Stormwater360, Filterra works like a traditional raingarden, with a fraction of its size.



A filterra bioretention system (Contech, 2020)

More information on the various projects Stormwater360 is involved with is available on its online platform.

- **Stormwater management by Contech Engineered Solutions**

Contech ES is a North American company that provides innovative, and cost effective stormwater treatment solutions for on-site stormwater management. One of their products is Stormwater Management StormFilter® - a rechargeable media-filled cartridge that can absorb and retain pollutants like TSS, hydrocarbons, nutrients, metals, and others. Contech's products are approved by the Washington State Department of Ecology (TAPE) GULD – Basic, Phosphorus, New Jersey Department of Environmental Protection (NJDEP), Canada ISO 14034 Environmental Management – Environmental Technology Verified (ETV), and Virginia Department of Environmental Quality (VA DEQ) amongst others. Contech also offers sizing methodology information for the design of the StormFilter® (Engineering Guidelines, Contech Engineered Solutions, 2015).

The Stormwater Management is an underground treatment structure containing cartridges filled with rechargeable media. Their design is derived from Stormwater360, New Zealand

An 8' x 24' Stormwater Management StormFilter with 60 cartridges is used to remove pollutants from runoff at Surfers Point Beach in Ventura, California (Contech, 2020)

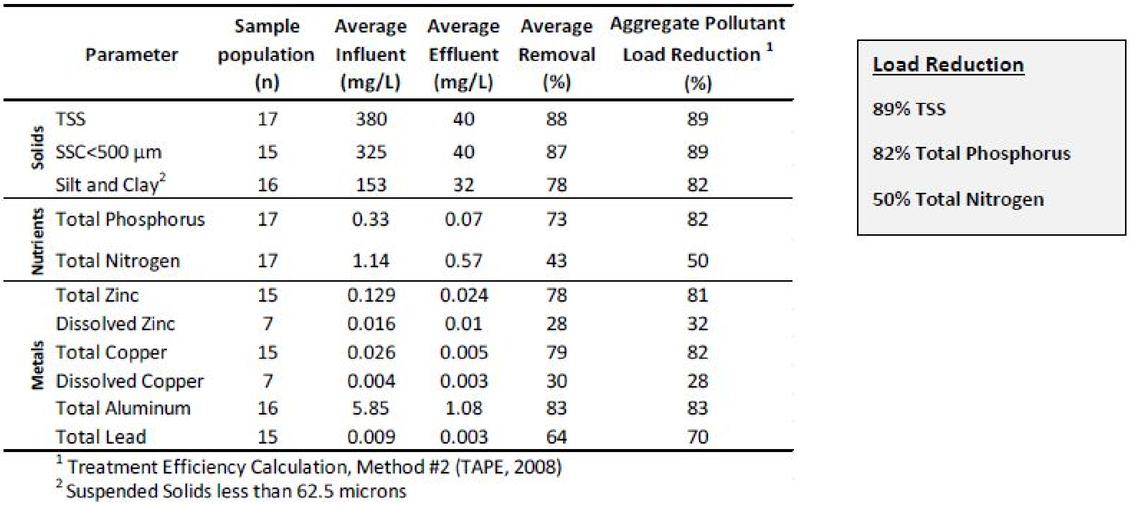
Cartridges filled with rechargeable media, used in Contech's stormwater management structures (Contech, 2020)

1. **Media available:**

Depending on the type of pollutant required to be removed, different media options are available from Contech like:

Media: PhosphoSorb

- Target pollutants: Dissolved phosphorus and particulate-P
- Key information: In 2012, a 3 year long pilot scale study was conducted with Stormwater Management StormFilter® with PhosphoSorb media operating with a flow rate of 1.67 gpm/ft2 at a 0.06 acre roadway site in Zigzag, Oregon. During the 37 month study, total volume of rainwater at site was recorded at 376,244 gallons. 4% of this volume bypassed the stormwater systems. 23 stormwater events produced peak flows exceeding design capacity of the system, requiring maintenance. Overall, the system required maintenance every 10-12 months, and retained an average of 291 pounds of sediment per maintenance event.



	Parameter	Sample population (n)	Average Influent (mg/L)	Average Effluent (mg/L)	Average Removal (%)	Aggregate Pollutant Load Reduction [1] (%)
Solids	TSS	17	380	40	88	89
	SSC<500 µm	15	325	40	87	89
	Silt and Clay[2]	16	153	32	78	82
Nutrients	Total Phosphorus	17	0.33	0.07	73	82
	Total Nitrogen	17	1.14	0.57	43	50
Metals	Total Zinc	15	0.129	0.024	78	81
	Dissolved Zinc	7	0.016	0.01	28	32
	Total Copper	15	0.026	0.005	79	82
	Dissolved Copper	7	0.004	0.003	30	28
	Total Aluminum	16	5.85	1.08	83	83
	Total Lead	15	0.009	0.003	64	70

[1] Treatment Efficiency Calculation, Method #2 (TAPE, 2008)
[2] Suspended Solids less than 62.5 microns

Load Reduction

89% TSS

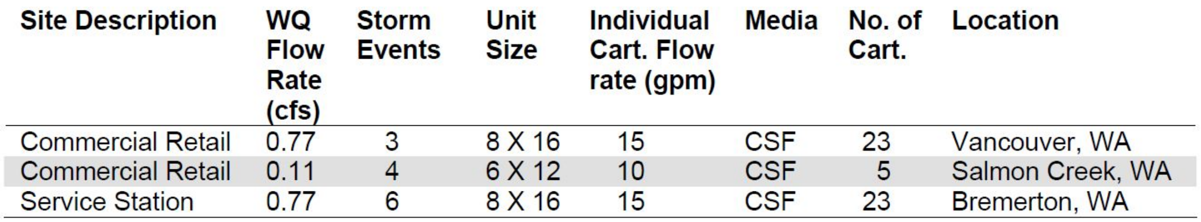
82% Total Phosphorus

50% Total Nitrogen

StormFilter with PhosphoSorb Field Evaluation Results (2015)

Media: CSF$^{®}$ Leaf Media and Metal RX$^{™}$

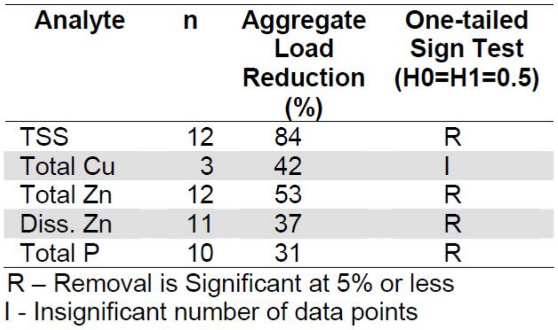
- Target pollutants: Soluble metals, TSS, and oils
- Key information: The CSF® leaf media, manufactured from leaf compost, was first used in a Washington County demonstration project in 1992. The Stormwater Management StormFilter® with CSF® leaf media was used in a field pilot study, with a flow rate of 10-15 gallons/min.



Site Description	WQ Flow Rate (cfs)	Storm Events	Unit Size	Individual Cart. Flow rate (gpm)	Media	No. of Cart.	Location
Commercial Retail	0.77	3	8 X 16	15	CSF	23	Vancouver, WA
Commercial Retail	0.11	4	6 X 12	10	CSF	5	Salmon Creek, WA
Service Station	0.77	6	8 X 16	15	CSF	23	Bremerton, WA

General Site Description of the field study (2006)

Data collected from 13 storm events yielded the following results:



Analyte	n	Aggregate Load Reduction (%)	One-tailed Sign Test (H0=H1=0.5)
TSS	12	84	R
Total Cu	3	42	I
Total Zn	12	53	R
Diss. Zn	11	37	R
Total P	10	31	R

R – Removal is Significant at 5% or less
I - Insignificant number of data points

Mean removal efficiency estimates (2006)

Media: CSF$^{®}$ Leaf Media and Metal RX$^{™}$

- Target pollutants: Soluble metals, TSS, and oils
- Key information: The CSF® leaf media, manufactured from leaf compost, was first used in a Washington County demonstration project in 1992. The Stormwater Management StormFilter® with CSF® leaf media was used in a field pilot study, with a flow rate of 10-15 gallons/min.

Media: Zeolite

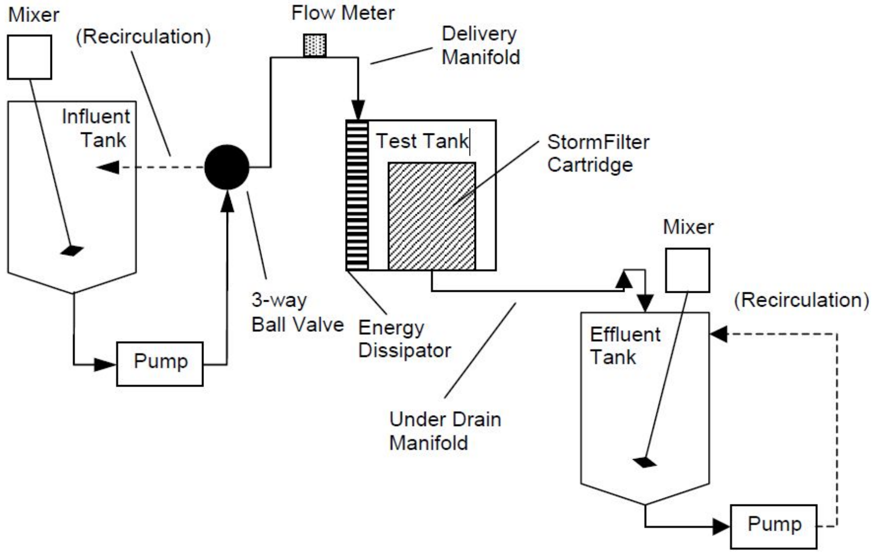
- Target pollutants: Soluble metals, ammonia, and some organics

Media: Granular Activated Carbon (GAC)

- Target pollutants: Oils, grease, and agricultural CECs (herbicides and pesticides)

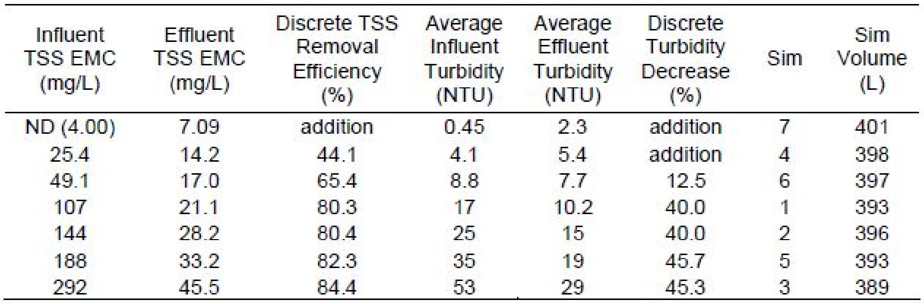
Media: ZPG™

- Target pollutants: Soluble metals, organics, and other pollutants



Schematic diagram of the cartridge-scale test apparatus (2004). Arrows indicate flow pathways. Dashed arrows indicate recirculation pathways employed during influent and effluent sampling.

Laboratory tests reported by Contech ES	Goal	To determine removal efficiency of a ZPG™ StormFilter cartridge
	Media	Proprietary blend of zeolite, perlite, and GAC, marketed as ZPG™ (as per Stormwater 360 product specifications)
	Target pollutants	TSS and turbidity; Surrogate for TSS: A commercial ground silica product, SIL-CO-SIL® 106 (SCS 106) (US Silica Company) from Mill Creek, OK plant. Particle size distribution was - silt texture (USDA scale) consisting of 20% sand, 80% silt, and 0% clay-sized particles
	Test apparatus	A typical proprietary Stormwater Management StormFilter® system.



Influent TSS EMC (mg/L)	Effluent TSS EMC (mg/L)	Discrete TSS Removal Efficiency (%)	Average Influent Turbidity (NTU)	Average Effluent Turbidity (NTU)	Discrete Turbidity Decrease (%)	Sim	Sim Volume (L)
ND (4.00)	7.09	addition	0.45	2.3	addition	7	401
25.4	14.2	44.1	4.1	5.4	addition	4	398
49.1	17.0	65.4	8.8	7.7	12.5	6	397
107	21.1	80.3	17	10.2	40.0	1	393
144	28.2	80.4	25	15	40.0	2	396
188	33.2	82.3	35	19	45.7	5	393
292	45.5	84.4	53	29	45.3	3	389

Summary of influent and effluent TSS EMCs and turbidity along with TSS removal and turbidity decrease results shown according to increasing influent TSS EMC (2004).

Conclusion

- A ZPG™ StormFilter cartridge test unit, operating at 28 L/min, and subject to TSS with a silt texture (20% sand, 80% silt, and 0% clay by mass) originating from SCS 106 provides a mean TSS removal efficiency of 87% (P=0.05: L1=86%, L2=89%)
- A ZPG™ StormFilter cartridge test unit, operating at 28 L/min, and subject to TSS with a silt texture (20% sand, 80% silt, and 0% clay by mass) originating from SCS 106 provides a mean turbidity reduction of 51% (P=0.05: L1=47%, L2=55%)
- A ZPG™ StormFilter cartridge test unit, operating at 28 L/min is effective on silica particles down to the 10 micron size range

The report acknowledges that the laboratory tests were performed under controlled conditions, and field conditions would vary with respect to TSS concentrations and sampling methods. The results from the laboratory study do not necessarily apply to the field.

2. **System configurations:**

Contech also offer various cartridge configurations best suited for the site and overall costs:

- 27” cartridge – Capitalizing on sites with at least 3.05 feet of available driving head, media surface area is maximized to allow the greatest treatment rate per cartridge; best for sites with footprint constraints
- 18” cartridge - The original StormFilter cartridge size provides a middle ground and operates with 2.3 feet of driving head
- Low Drop – Provides filtration treatment with only 1.8 feet of headloss; best for sites with limited by hydraulic constraints

Contech also offers stormwater treatment structure configurations that offer flexibility in flow accommodation, project footprint, and hydraulics:

- **The Peak Diversion StormFilter:** provides treatment and high flow bypass in one precast vault, eliminating the need for an external bypass or junction structures.
- **The Volume StormFilter**: designed to meet volume-based treatment regulations and can be combined with upstream storage to treat and drawdown the water quality volume within the required drain down time.
- **The Cast-in-Place StormFilter** structure: allow the highest degree of flexibility and are available for installations within buildings or other areas where precast structures cannot be accommodated. On-site Contractor assistance is provided to ensure the finished product meets Contech’s standards for fit and function.

3. **System Maintenance:** In terms of maintenance, Contech claims that their products have maintenance intervals of 1-5 years, resulting in reduced life cycle costs. They are easy to maintain and inspect. They also offer a cartridge replacement program for media replacement.