Prepared for: City of Fort Collins

Bioretention Media Mixtures – A Literature Review

Prepared by:

Tyler Dell

Jason Brim

Colorado Stormwater Center
One Water Solutions Institute
Colorado State University

Department of Civil and Environmental Engineering

June 23, 2017

1372 Campus Delivery, Fort Collins, Colorado 80523
Voice: 970.491.8015

Table of Contents

FIGURES AND TABLES

FIGURES

TABLES

1.0: INTRODUCTION

The City of Fort Collins now requires that Low Impact Development (LID) be utilized on all new and re-developments. Bioretention is one LID technique that is being used extensively across the nation in locations like Portland, Oregon (City of Portland 2006) and Philadelphia, Pennsylvania (Philadelphia Water Department 2017), and is also referenced as an applicable LID technology to meet LID requirements in Fort Collins (Council of the City of Fort Collins 2012). Bioretention removes pollutants from stormwater by filtering the stormwater through a filter media layer. For the City of Fort Collins, bioretention sand media (BSM) is specified to contain 60-70% sand, 5-10% shredded paper, 5-10% topsoil, and 10-20% leaf compost (City of Fort Collins 2011). The City of Fort Collins has worked with the Colorado Stormwater Center for a previous monitoring effort at the 700 Wood St. bioretention cell where results suggest that the current media is not very effective a removing nutrients. Due to the lack of removal efficiency of the City's current mixture specifications, the City is considering modifying its requirements for bioretention media to increase the removal of nutrients. As a first step toward modifying the bioretention media requirements, the City requested that a literature review be conducted of regarding what other bioretention media mixes are being used and how effective those media are at removing nutrients, particularly phosphorus.

The goal of this literature review was to provide the City with options to improve their current bioretention media mix to enhance the removal of nutrients. The primary focus of this study was placed on mixes that provided phosphorus removal. The report summarizes the results (e.g. nutrient removal effectiveness, media type, design life) of identified peer-reviewed studies that have quantified nutrient removal of filter media in both field and lab studies.

Conclusions from the report include the need for the City of Fort Collins to re-evaluate the use of compost in their current bioretention sand media. It is instead recommended to use shredded mulch as an organic matter source similar to the urban drainage and flood control district volume 3 stormwater manual. It was also determined that the use of alum-based water treatment residuals to prevent phosphorus leaching is worth further investigation and should be considered for a field test at a stormwater facility in Fort Collins

2.0: Summary of Results

This section provides a summary of the most important findings of this review. Included in this section is the background of the project, a summary of the use of compost in bioretention media, a summary of the bioretention media mixes reviewed, phosphorus performance regarding the mixes, other considerations beyond performance for media mixes, and additional information regarding the use of water treatment residuals (WTRs) for stormwater pollutant reductions.

2.1: Background

The Colorado Stormwater Center has partnered with the City of Fort Collins to monitor the effectiveness of the current bioretention media mix for nutrient treatment in urban stormwater. Results from the monitoring effort revealed that the average influent concentration of total phosphorus (TP) and dissolved phosphorus (DP) are about 0.3 mg/L and 0.2 mg/L, respectively. The average effluent concentration of TP ranges from about 0.6-0.9 mg/L and for DP the average effluent concentration ranges from 0.45-0.65 mg/L. These results, displayed in Figure 1, indicate that phosphorus is being exported from the bioretention cell (BRC). In other words, there is a relatively significant source of phosphorus within the BRC that is leaching phosphorus into the runoff as is moves through the BRC.

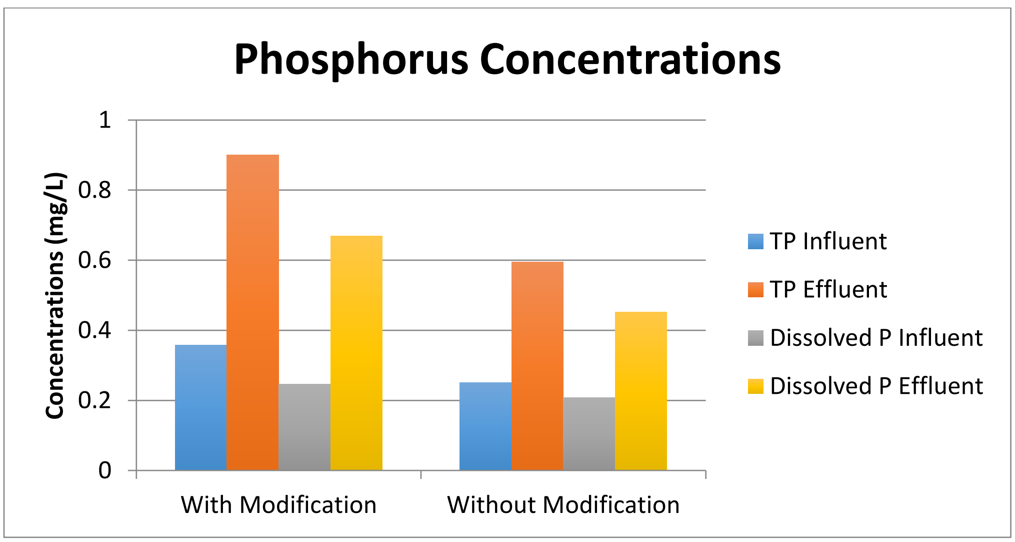

Figure 1: Average total (TP) and dissolved (DP) phosphorus concentrations measured at the inlet (influent) and in the underdrain (effluent).

The current mix used by the City of Fort Collins includes 60-70% sand, 5-10% shredded paper, 5-10% topsoil, and 10-20% leaf compost by volume (City of Fort Collins 2011). Since this mix has been determined through monitoring to be a source of total and dissolved phosphorus, alternative mixes are being evaluated. The following review includes probable reasons for the phosphorus leaching experienced with the current mix and potential solutions to modify the mix and/or include additives to mitigate the leaching of phosphorus.

2.2: Compost in Bioretention

Research conducted by Hurley et al. (2017); Logsdon and Sauer (2016); Mullane et al. (2015); and Paus et al. (2014) have shown that compost in bioretention media mixes can become a significant source of phosphorus leaching and should be mitigated using secondary layers of media, applying additional additives such as WTRs to the media mix, or simply reducing or eliminating the use of compost in bioretention media altogether. Compost is used in bioretention media to provide an adequate food source to establish vegetation. Urban Drainage and Flood Control District in their Urban Stormwater Drainage Control Manual Volume 3 suggests using 3-5% (by weight) shredded mulch as an alternative to leaf compost (UDFCD 2011). In North Carolina, it is recommended to use 3-5% organic matter consisting of newspaper mulch, or in some cases in North Carolina, peat moss was used (Hunt and Lord 2006). Other states such as Minnesota continue to recommend using 15-25% compost, however, they add the disclaimer that mixes containing those amounts of organic matter will probably leach phosphorus and should be sampled to determine the phosphorus discharge will not impact water quality.

2.3: Summary of Reviewed Mixes

The literature review for bioretention media mixes (BMM) was conducted by looking at primary sources and secondary sources of peer-reviewed studies. Primary sources included studies that were conducted by the author regarding the performance of bioretention mixes and additives for phosphorus removal. Secondary sources composed of other literature reviews that were conducted regarding the performance of bioretention media mixes. Both primary and secondary sources were used to evaluate the general performance of different BMM regarding hydraulic conductivity, pollutant removal, design life, and rehabilitation.

Bioretention cells must allow water to pass through the media, requiring high measures of hydraulic conductivity corresponding to high infiltration rates (Hsieh and Davis 2005). Due to this, sand is a primary ingredient in bioretention media mixes. However, to promote vegetation, finer particulates are also required for water and nutrient detention. Finer particulates are added as sandy loams, silts, clays, and top soil (City of Fort Collins 2011; Hunt and Lord 2006; Minnesota Pollution Control Agency 2017; UDFCD 2011). These components of BMM have been found to be consistent across several design criteria, though the proportions may change, each criteria includes sand and some finer soil particles. What differentiates the treatment capabilities of BMM are the additives that are included to different mixes to perform particular functions. Additives are used in BMM to promote vegetation growth, remove targeted pollutants, or even increase hydraulic conductivity.

From a review of design manuals, BMM require a source of organic carbon for plant growth generally accomplished through the inclusion of compost, shredded mulch, paper, or others. As mentioned above, some of these additives, compost in particular, can result in large amounts of nutrient being leached (Hurley et al. 2017). A study conducted by Soleimanifar et al. (2016), included the use of wood chips to BMM in order to increase the hydraulic conductivity of the BMM while simultaneously providing a carbon source. Finally, as seen through the following primary and secondary sources, additives have also been used to target a particular pollutant.

Additives used to target pollutants of interest were condensed to four categories. The first category included natural materials such as compost, mulch, paper, coconut fibers, and varying types of minerals. Water treatment residuals composed the second category and was the main additive evaluated for reasons discussed below. A newer additive, biochar, was the third category. Biochar is created through pyrolysis transforming biomass such as wood pellets or wood chips into biochar (Laird et al. 2009). The final category for this literature included the use of industrial by-products (i.e. fly ash, blast/oxygen furnace slag, concrete waste, etc.) for BMM. Table 1 displays the number of primary and secondary sources that discussed each category of BMM additive. This study did not evaluate activated carbon due to its high cost and short design life.

Table 1: Quantification of primary and secondary sources reviewed which discussed each category of BMM additive

Type of Mix	# of Primary Sources Reviewed	# of Secondary Sources Reviewed
Natural Materials	5	2
Water Treatment Residuals (WTRs)	17	5
Biochar	4	-
Industry By-Products	2	5

2.4: Evaluation of Additives to Bioretention Media Mixes (BMM)

The review focused on additives for pollutant removal that specifically targeted phosphorus. In 2012, the Colorado Department of Public Health and Environment (CDPHE) advanced the enforcement of nutrients through "Regulation 85-Nutrients Management Control Regulation" (Reg. 85) (Colorado Department of Public Health and Environment 2012) to provide numeric nutrient discharges limits from wastewater treatment plants. In 2016, CDPHE issued a new general MS4 permit (Colorado Department of Public Health and Environment 2016) for Phase II MS4's that requires permittees to provide education and outreach on nutrient discharges in urban stormwater and to implement control measures for municipal operations and facilities to prevent or reduce nutrients in stormwater runoff. The City of Fort Collins is a Phase II MS4 permittee and therefore must meet these requirements. Additionally, it was discovered from the past monitoring effort, the measure that was being adopted to treat stormwater pollution was potentially exacerbating the problem in regard to phosphorus leaching. Finally, all of this combines into the City's desire to continue to improve and protect the surrounding water bodies from potential harmful pollution. Therefore, the pollutant of interest for the review was phosphorus. Phosphorus removal efficiencies were found from peer-reviewed studies for each of the four categories of additives shown in Table 1 and are summarized below.

2.4.1: Natural Materials

The first additive that was reviewed was natural materials that have been included into BMM. From literature there were multiple types of natural materials that have been included into BMM and the results have been varying when it comes to phosphorus removal. Hunt et al. (2006) studied the effects of three different sandy medias as fill material each with a different P-index. The phosphorus removal ranged from 65% removal to a 240% increase. Findings from this study showed that P-indexes of soils should remain low with high cation exchange capacity in order to prevent leaching of phosphorus. Studies conducted applying biosolids and compost to BMM were consistent in showing that amounts of compost greater than 10% resulted in an increase in phosphorus, however, compost was found to provide heavy metal reduction (Agyin-Birikorang et al. 2008, Paus et al. 2014). Use of compost with an addition of crushed cockle shell displayed a 95.6% reduction of phosphorus in a study conducted by Goh et al. (2015). Lim et al. (2015) evaluated the use of coconut fibers for BMM. Though they did not measure the impacts of coconut fibers on phosphorus, the study found that coconut fibers performed similar to compost for the reduction of heavy metals and could be an alternative to compost.

Overall the use of natural materials is appealing as a treatment option because of their nature of being a natural not man-made material. However, there are varying results regarding the effectiveness of natural materials for phosphorus reduction and the studies that have shown high removal efficiencies have not been replicated enough to attempt a full site scale test. Natural materials have consistently shown to provide very high heavy metal reduction and should be included in any BMM mix that is trying to meet a heavy metal TMDL. However, if nutrient reductions are desired, then the use of natural materials, particularly compost, should be reduced below 10% of the BMM and/or substituted with other organic materials such as shredded mulch to reduce the leaching of phosphorus.

2.4.2: Water Treatment Residuals (WTRs)

Water treatment residuals (WTRs) are by-products of water treatment for drinking supply. WTRs contain precipitated aluminum and/or iron oxyhydroxides which has a strong affinity for anionic species such as dissolved phosphorus (Ippolito et al. 2011). There have been numerous studies evaluating the effectiveness of WTR for phosphorus removal in runoff. 17 primary source studies and 5 secondary source studies were reviewed to provide a comprehensive look at this technology.

Section 3.1.6 – Section 3.1.22 contain a summary of each of the primary sources reviewed that used WTR. Included in the summaries are the application rates of WTR, the capacity of WTR for phosphorus sorption and removal efficiency of WTR for phosphorus when available. From the studies, there was a variation of removal rates that was witnessed, however, this was directly linked to varying application rates, residence times, and/or phosphorus sorption capacity of the WTR. Table 2 displays the summary for the performance of several of the studies regarding the application, capacity and removal efficiency of WTRs.

Table 2: Effectiveness of Phosphorus Removal and Storage Capacity for Water Treatment Residuals (WTRs)

Study / Amendment	Al-WTR	Fe-WTR	AL+Fe-WTR	Fe+CaO-WTR
Mortula et al. 2006	Application: 4-16 g/L Removal: 94-99%			
Oladeji et al. 2007	Application: 10 g/kg Removal: 46.2-53.7%			
Zhao et al. 2007	Removal: 90.5 %			
Babatunde et al. 2009	Capacity: 31.9 mg P/g Removal: 87-97%			
Zhao et al. 2010	Capacity: 0.025-32 mg P/L Removal: 94.6%			
Ippolito et al. 2011	Capacity: 3.5-12.5 mg P/g Removal: 99.6%	Capacity: 2-9.1 mg P/g		
Stoner et al. 2012	Removal: 10-50%			
Habibiandehkordi et al. 2014	Capacity: 13.7 mg P/g	Capacity: 2.4 mg P/g		Capacity: 9.3 mg P/g
Liu and Davis 2014	Application: 5% of BMM Reduction: 55.1%			
Bai et al. 2014			Capacity: 7.42 mg P/g Reduction: 98%	
Castaldi et al. 2014	Removal: 50%	Removal: 50%		
LeFerve et al. 2014	Removal: 95-99%			
Ippolito et al. 2015	Application: 62 Mg/ha Capacity: 2.343 mg P/g Removal: 60%			
Habibiandehkordi et al. 2015	Application: 20 metric tons/ha Removal: 65.6-68.4%			
Soleimanifar et al. 2016	Application: 10 g/L Capacity: 0.22 mg P/g Removal: 97%			
Liu et al. 2016	Removal: 75-99%			

From the many studies reviewed it was sufficiently determined that WTRs could reduce the leaching of phosphorus, particularly dissolved phosphorus. However, the retention/removal provided by the WTR is directly dependent on how much WTR is applied and the phosphorus sorption capacity of the WTR which can vary from source to source. The Fort Collins WTR has been reviewed in a previous study and shown to provide a phosphorus sink (Bayley et al. 2007), however the actual capacity for retaining phosphorus has not yet been quantified but will be soon by Dr. Jim Ippolito at Colorado State University. Not only has the Fort Collins WTR been shown to be a phosphorus sink, it has also been shown to remain being a sink over the course of a 13-year period with only two applications over the 13 years (Bayley et al. 2007).

Phosphorus is not the only pollutant that has been treated by WTRs, but it is the most prevalent. Research completed by Bai et al. (2014) has shown WTRs to be able provide additional removal of nitrogen suspended solids and chemical oxygen demand. Ippolito et al. (2011) found that WTRs could provide sorption of perchlorate (ClO_4), selenium (Se), Arsenic (As), and Mercury (Hg) at varying levels of effectiveness. Zhao et al. (2007), displayed the abilities of WTRs to provide treatment for suspended solids, chemical oxygen demand and biological oxygen demand in addition to phosphate. Figure 2 contains a set of graphs from the experimental results of horizontal flow through vegetated sludge containing WTRs from Zhao et al. (2007). From the figure, there is a substantial reduction in concentration for each of the pollutants evaluated. Additionally, over the course of almost 200 days, the WTRs continued to function at a steady rate without signs of increases in leaching.

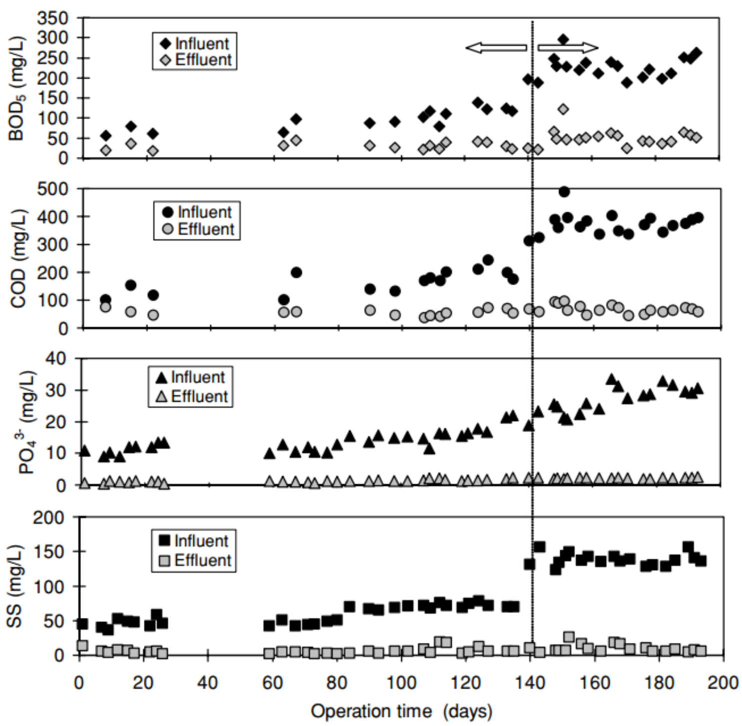

Figure 2: Experimental results of horizontal flow through vegetated sludge containing WTRs in a wetland from Zhao et al. (2007)

Not only does it appear that WTRs provide a promising additive to use in BMM, but it also provides a sustainability component. Currently WTRs are seen as a waste/by-product of the water treatment process and in most cases, are sent to a landfill for removal. Providing an opportunity for these materials to be re-used for stormwater treatment could help cities limit the amount of material needed to purchase for bioretention media while simultaneously reducing the waste from water treatment facilities

There are some concerns in using WTRs as an additive in BMM. The first is the need to monitor the release of heavy metals, particularly aluminum for Al-WTRs. Heavy metal release has been shown to be minimal (< 0.5 mg/L safe for aquatic life) at circumneutral soil pH conditions (Ippolito et al. 2011, Liu et al. 2016, and Mortula et al. 2006). Another concern when using WTRs is ensuring that there is still enough phosphorus available for plants sustained by the soil media. Oladeji et al. (2007) found that applications rates less than 10-15 g WTR/kg soil will allow for the soil media to support vegetation growth. It is crucial to ensure that water can continue to pass through the filter media at the required rates for stormwater management. The literature reviewed for this study did not show any substantial reduction in hydraulic conductivity by adding WTRs. However, in the case that adding WTRs did limit the hydraulic conductivity beyond target levels it has been proposed that some of the benefits of WTRs could still be experienced by coating mulch with WTRs and adding the mulch to the BMM (Soleimanifar et al. 2016). Finally, WTRs when removed from water treatment facilities are generally saturated and would need to be able to be stored to allow for the material to dry-out.

2.4.3: Biochar

Biochar is created through pyrolysis, transforming biomass such as wood pellets or wood chips into biochar (Laird et al. 2009). Biochar is a relatively new additive that is being evaluated for use in treating stormwater runoff. Studies conducted by Rozari, (2016) and Reddy et al. (2014) both displayed promising results for the removal of phosphorus and in particular dissolved phosphorus by using biochar, reporting removal rates between 43-92% for phosphate. However, Afrooz et al. (2017) reported much lower removal rates (18.8-21.9% +/- 14%), and Ulrich et al. (2017) determined that in some cases the biochar leached dissolved phosphorus (Figure 3). Reddy et al. (2014) proposed the removal of phosphates from the use of biochar is lower than for water treatment residuals as a result of the overall negative charge for the biochar constituents compared to the overall positive charge of the water treatment residuals constituents.

Ulrich et al. (2017) showed biochar to provide increased removal in total organic carbon, total nitrogen, nitrate, some metals, and E. Coli. Afrooz et al (2017), Rozari (2016), and Reddy et al. (2014) all concluded with the need for further research to understand the best mixes of biochar to use for different BMM. Due to the variability and uncertainty in biochar, it is not recommended that the City of Fort Collins pursue this option for field study until more conclusive laboratory studies have been conducted.

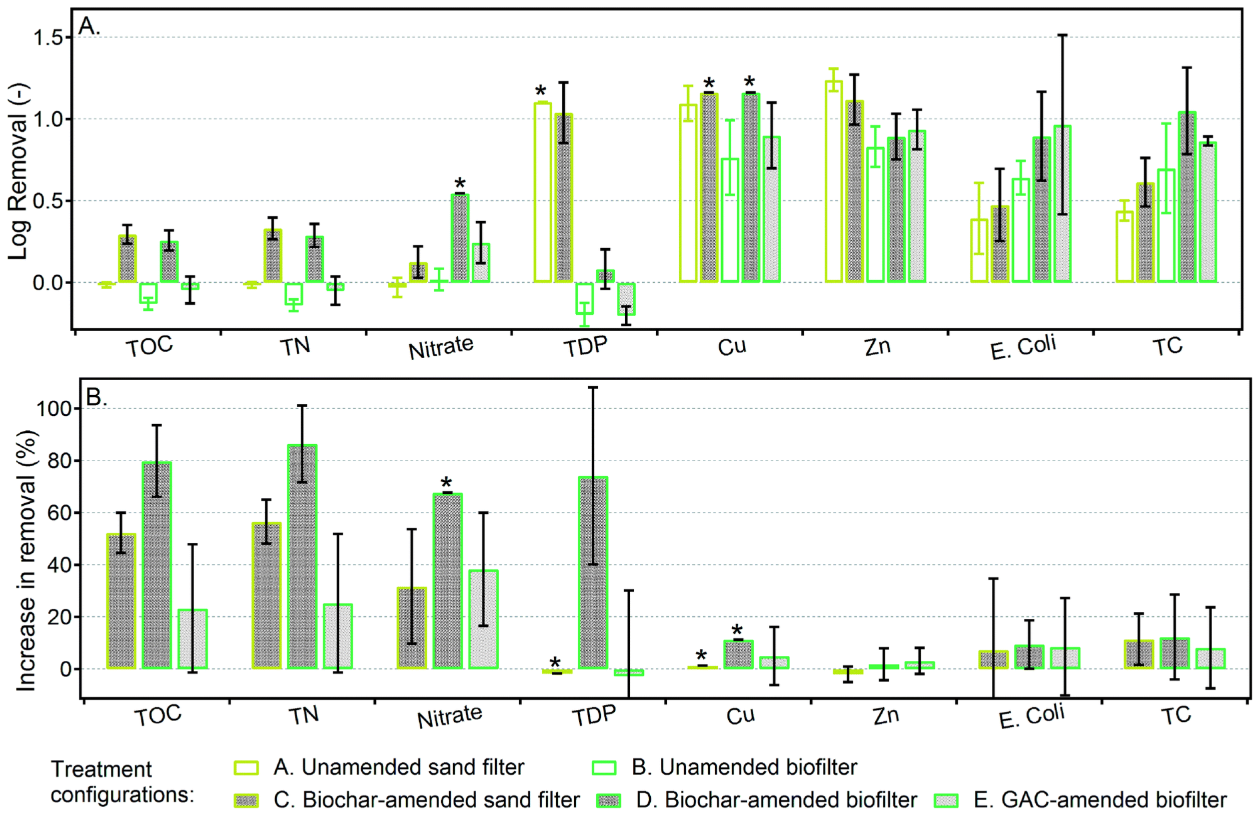

Figure 3: (A) Log removal (-log[$C_{effluent}/C_{influent}$]) for TOC, nutrients, metals, and indicator bacteria among the treatment configurations during the final high-volume dosing experiment (a negative log removal represents a load increase in the effluent). Asterisks indicates cases where effluent contaminant concentrations were below detection limits. (B) Percent increase in contaminant removal due to sorbent amendment (i.e., percent removal in sorbent-amended configurations, minus the percent removal in unamended configurations).

2.4.4: Industrial By-Products

The final category for this literature included the use of industrial by-products for BMM. Some common types of industrial by-products include blast/oxygen furnace slag (steel production), cement dust (cement production), fly ash (coal combustion), and ochre (mining).

Agrawal et al. (2011) showed that blast furnace slag and a 5:95% cement kiln dust (CDK) to sand ratio had the potential to remove >98% of phosphates. The study additionally showed that at higher ratios of CDK to sand (10:90%) reduced hydraulic conductivity to below 0.001 cm/s (< 1.5 in/hr). Dunets et al. (2015) evaluated the effectiveness of oxygen furnace slag and concrete waste for removing phosphorus and found that for a 3-hour retention time was able to remove 99% of phosphorus when dosed with 20 and 60 mg P/L greenhouse wastewater. Vohla et al. (2011) determined that notable industrial byproducts fly ash, ochre, basic oxygen furnace slag, and blast furnace slag removed 83%, 90%, 90.4%, 85.6-95% of phosphorus.

Overall, from the reviewed studies it appears that industrial waste products could potentially provide the necessary phosphorus treatment, but it is still uncertain what materials may leach into the water from using these by-products. Also, like WTRs, industry by-products provide the additional opportunity to turn wastes into resources. However, unlike WTRs, municipalities may have limited access to these by-products. If the City of Fort Collins does have a ready available supply of some of these industrial by-products it could be worthwhile to evaluate their use at a facility within Fort Collins, but WTRs remain the lead candidate for a site study.

2.5: Using Water Treatment Residuals

After reviewing numerous articles regarding different additives that could be used for phosphorus reduction for Bioretention Media Mixes (BMM), it was determined that Water Treatment Residuals (WTRs) would be the most beneficial. WTRs were further evaluated for application at a stormwater detention facility in Fort Collins. Using WTRs in Colorado will require the completion of two procedures. The first procedure requires the calculation of necessary application of WTRs in order to achieve phosphorus reduction goals. The second procedure involves the regulatory requirements for using WTRs. For both processes, Dr. Jim Ippolito, a soils professor at Colorado State University was consulted, and he supplied the necessary information to perform the calculations, a process outlined in Ippolito et al. (2015), and summarized below, as well as insight into the regulatory requirements for WTRs.

2.5.1: WTR Application Rate

Determining the amount of WTRs required for phosphorus treatment for the stormwater facility began by calculating the total dissolved phosphorus expected to be received by facility. WTRs were evaluated for application at an extended detention basin (EDB) in Fort Collins that had a surface area of approximately 1.3 acres and drained a basin of approximately 640 acres. The drainage basin was determined to contain 36.6% impervious surfaces from NLCD 2011 data corresponding to a water quality capture volume depth of 0.17 inches using Equation 1.

Equation 1

$$WQCV = a(0.91 * I^3 - 1.19 * I^2 + 0.78 * I)$$

Where: a = Coefficient responding to WQCV drain time (1.0 for EDB)

I = Imperviousness (%/100)

The EDB is designed to be able to capture and treat the WQCV for each runoff producing event and in Colorado there are approximately 29 runoff producing events per year (UDFCD 2011). This corresponds to a total annual capture depth of 4.95 in/yr. Distributed across the entire drainage area results in an annual treatment volume of 264 acre-feet of water. To determine the amount of dissolved phosphorus that must be treated for this volume it was necessary to multiply the volume by the average dissolved phosphorus concentration in runoff which from the monitoring study was found to be approximately 0.2 mg/L. This corresponds to approximately 100 lbs of dissolved phosphorus that must be treated by WTRs per year. Assuming an average sorption capacity of 2000 mg P/kg WTR it was found that treating the dissolved phosphorus in the WQCV would require 25 tons of WTRs/year corresponding to a loading rate of 42 Mg/ha/yr, or 207 Mg/ha/5 years.

2.5.2: Regulatory Requirements for WTRs

After calculating the total amount of WTRs necessary to treat the WQCV for the stormwater drainage area, there was an additional component to using WTRs that involves regulatory requirements. Since WTRs are a by-product of water treatment, users of WTRs must obtain permission to use WTRs from the state health agency, Colorado Department of Public Health and Environment (CDPHE). The first step to obtaining permission to use WTRs involves submitting a beneficial use plan to CDPHE. The plan must include

- A legal description of the planned application site.
- The name or address of the producer, any contractors, and the user.
- The application rate in pounds per acre.
- The types of crop to be grown at the application site.
- The number of acres of crop type.
- Landowner approval for the land application of WTR and permission to enter the site to preform monitoring.
- Analyses of the WTR for the parameters in Table 3.
- A detailed monitoring plan that also addresses actions to identify and remediate any negative impact from the application of WTR.
- Issuing notice to the local health department of the development.
- Any other information the Department deems relevant to impacts on human and environmental health. (e.g., analyses for speciated radionuclides Radium-226, Radium-228, Uranium-235, Uranium-235, Uranium-238, and Thorium-232, depth to seasonally high groundwater table (minimum 3')).

Table 3: Analyses and reporting units for using WTRs

Parameter	Units	Parameter	Units
Total Solids	Percent	Total Chromium	mg/kg
pH	Standard Units	Total Copper	mg/kg
Organic-N	Percent	Total Iron	mg/kg
Total Ammonia-N	Percent	Total Lead	mg/kg
Nitrate-N	Percent	Total Mercury	mg/kg
Total Phosphate	Percent	Total Molybdenum	mg/kg
Total Potassium	mg/kg	Total Nickel	mg/kg
Total Aluminum	mg/kg	Total Selenium	mg/kg
Total Arsenic	mg/kg	Total Zinc	mg/kg
Total Cadmium	mg/kg	Total Alpha Activity	pCi/g

* All results expressed in dry weight basis for composited sample

After submitting the beneficial use plan, CPHDE could request extra monitoring if it is thought that the WTR may have other materials of concern (i.e. speciated radionuclides). Once a baseline profile of the WTR is established, composite sampling and analyses must be completed annually. (If there is a change of process in the production of the WTRs, the water treatment plant must characterize the new residual and submit a new Beneficial Use Plan to CDPHE.) In 30 days, CDPHE will decide if the plan is beneficial. Once the plan is cleared, CDPHE will try to submit approval within 30 days. The beneficial use plan must be sent to the local governing authority to notify them. The local governing authority can deny the plan even if approved by CDPHE. CDPHE then issues a Beneficial Use Determination ("BUD") or Certification after final review and approval. The certification approves the beneficial use of the water treatment residuals at the location indicated in the plan. Separate beneficial use plans should be submitted to the Division for each location where WTR would be applied. Any costs accumulated during the completeness review and comprehensive technical review of the plan will be paid by the applicant.

The beneficial use plan could be bypassed and the land application of WTR could be granted under a general permit if the nature of the WTR is described (process used that produces it), and documentation of the site is provided including area and volume of the BMP. This permit would be a permit to discharge to a surface body of water if regulations regarding discharge into a surface body of water are maintained. Once both processes have been completed and finalized the use of WTRs could begin for a stormwater facility.

2.8: Conclusions and Recommendations

After reviewing several peer-reviewed studies which investigated the phosphorus removal efficiencies of various types of additives to bioretention media mixes the maximum amount of phosphorus sorption capacity needs to be kept in mind. Although some of the natural materials can have a high removal efficiency, they typically vary widely on phosphorus sorption capacity and can even become phosphorus sources. The phosphorus sorption capacity of a material will decide effectiveness and the design life of the media. Therefore, a higher sorption capacity typically means a longer design time and more phosphorus removal. The high phosphorus removal and high phosphorus sorption capacity of the WTR's is what makes them a viable option for long term phosphorus removing amendments to bioretention media. Biochar and industrial by-products showed similarly high sorption capacities, but due to the variability and uncertainty in the performance in biochar and the potential lack of availability of industrial by-products, WTRs are the recommended bioretention media mix additive to further investigate.

One current site that could potentially evaluate the effectiveness of WTRs is the Locust pond extended detention basin that also serves as a partial wetland. Initial calculations presented in Section 2.7 reflect that a loading rate of approximately 210 Mg/ha of WTRs would be required in the facility to provide 5 years of treatment for the water quality capture volume. Dr. Jim Ippolito is currently undergoing research regarding the removal capacity of the aluminum based WTRs (AL-WTRs) available from the Fort Collins facility and once the capacity is known, final loading rates for the facility can be calculated. In order to use WTRs however, the regulatory procedure must be completed.

Another finding from this review is the need to reduce and potentially remove compost from the City's current BSM. Reduction and/or removal of compost is a direct result of findings from the monitoring effort of the Wood Street site as well as a review of literature demonstrating the tendency of compost to leach dissolved phosphorus into the effluent of bioretention cells. It is recommended to reduce the amount of compost below 10% or even more preferable to adopt a similar mix as Urban Drainage and Flood Control District in their volume 3 manual which removes compost completely and replaces with additional silts and clays and 3-5% shredded mulch.

A final strategy that the City may wish to investigate as well is the use of layered systems. Layered systems are currently being studied in Minnesota and are designed to minimize phosphorus in bioretention effluent. The Wisconsin layered system utilizes a five-inch surface layer containing 20 percent compost, a 10-inch sand layer below the surface layer, and a 10-inch lower layer containing five percent iron filings. Some advantages of using this system include: compost only being utilized in the part of the soil necessary to provide healthy plant growth and can still provide heavy metal removal. By using sand below the compost, you reduce the amount of compost in the media where it is not needed for vegetation and can reduce potentials for leaching of phosphorus. Finally, the bottom layer of iron filings could provide phosphorus sorption in case any phosphorus did leach from the top compost layer. Disadvantages of this procedure include higher costs of installation due to layering, greater potential for installation error, and additional risk for inadequate plant growth from the limited depth of organic matter (Minnesota Pollution Control Agency 2017).

In closing, there are some additional management recommendations/observations that were found in the Washington manual which may be of interest to the City as they are very practical. If compost is used, phosphorus can be managed in bioretention media through using mature stable compost to help reduce leaching, and a healthy plant community can provide direct phosphorus uptake. Increasing the media column depth to 24 or 36 inches can provide additional contact time for greater phosphorus sorption in the soil. Metal oxides such as iron, aluminum and calcium can be added to increase the amount of phosphorus that can be absorbed which is why adding WTRs is effective as they contain these metal oxides. Sandy gravel filter bed materials for the underdrain provides a final filter for fine particulates and provides additional binding sites for phosphorus (Carlson et al. 2013).

Overall, the use of additives for phosphorus control has been a large topic of research in the stormwater community and as more studies come out it is important to remain informed for those seeking to use these additives. The work that is being conducted with biochar is of particular interest as that emerging technology shows promise for multiple reductions of pollutants. Though there have been many studies conducted, the wide-scale adoption of several of these additives are still far behind making it necessary for communities to take the lead and testing and evaluating different additives and mixes in the real world.

3.0 Literature Review Summaries

This section describes the studies reviewed for the use of water treatment residuals, coconut fibers, biochar, and other bioretention filter media in removing phosphorus from storm water and wastewater. The review includes primary sources and secondary sources that address removal efficiency, design life, unintended consequences, maintenance requirements, and types of mixes used.

3.1 Primary Sources

Primary sources include studies that directly evaluated the performance of bioretention media mixes and studied the pollutant removal effectiveness of the mix used.

The information in this section summarizes each literature source based on available information regarding the location(s) of the projects, type of bioretention mixes used, pollutants targeted for removal, effectiveness of removal for targeted pollutants, design life of mix applied, necessary maintenance requirements, unintended consequences, and the human and environmental impact of applied bioretention mixes.

Sand Media with Compost/Mulch/Coconut

3.1.1: Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina (Hunt et al. 2006)

Three bioretention field sites in North Carolina were evaluated for pollutant removal capacities and hydrologic performance. The first cell, C1 was backfilled with a sandy media mined from a local quarry. Cell G1 and G2 contained locally available organic sandy soil. Bioretention mass removal rates for TP at the field sites ranged from a 65% removal to a 240% increase, probably due to the type of media used in the bioretention cell. The phosphorus index (P-index) of the media in cell G2 was high (86 to 100), indicating that the media was saturated with phosphorus. In cell C1, the P-index was low (4 to 12), indicative of a media that could accept more phosphorus. In cell G1 the P-index was also low - medium (20 to 26). The lower P-index, with more available cation exchange capacity (CEC) sites, likely enhances the adsorption of phosphorus, thereby lowering the TP concentrations in the outflow. Soil media of this composition are recommended for use in phosphorus-sensitive watersheds.

3.1.2: Evaluating phosphorus loss from a florida spodosol as affected by phosphorus-source application methods (Agyin-Birikorang et al. 2008)

This study evaluated the P-loss potential of Florida spodosols (Immokalee fine sand, sandy siliceous hyperthermic Arenic Alaquods) that have been amended with biosolids (P-source).

In the study phosphorus, was applied in a simulated rainfall event at a constant rate of 224 kg/ha. It was found that Lakeland, Orange County, and Gainesville biosolids had high P leaching while the Disney, and Milograntie biosolids produced low P losses in the spodosol sands. A strong positive correlation between P load by mass of the sources and P losses by mass with rainfall were recorded. There was more P leaching when P loads were higher. The study ended by addressing that soil amendments would be necessary to reduce P-losses in Florida spodosols.

3.1.3: Effects of bioretention media compost volume fraction on toxic metals removal, hydraulic conductivity, and phosphorous release (Paus et al. 2014)

This study investigated the effects of the compost fraction in bioretention media on toxic metal removal, hydraulic conductivity, and phosphorus release. This study was conducted in Minneapolis, Minnesota.

The compost used was derived from leaves, grass, and woody debris. A column study was done with 5.08cm diameter and 30.5cm length PVC pipes. 15cm of dry bioretention media was placed in three 5cm sections separated by 2.5cm layers of sand. Ratios of 10:90%, 30:70%, and 50:50% compost to sand mixtures were used, and a 100% sand column was used as a control. These ratios come out to be 4, 14, and 27% compost per total mass of the system. A 4cm deep bed of pea gravel at 10mm was added to the bottom and top of each column to evenly distribute flow and support the bioretention media. A higher percentage of heavy metal removal was observed with a higher mass percentage of compost. However, 203 ± 24 mg of P per kg of compost was released. For the 10:90% ratio for compost to sand media particulate P was filtered but dissolved P was not, and for both the 30:70% and 50:50% ratios both particulate and dissolved P were released. Compost has the ability to retain metals but will release a significant amount of phosphorus which creates a concern for bioretention cells aimed at removing phosphorus. It is recommended that if compost is to be used in a bioretention cell that compost should be placed on the top layer to retain metals, and filter media amended with phosphorus removing materials should be placed below the compost to remove phosphorus that has been released from the compost.

3.1.4: Influence of hydraulic conductivity and organic matter in different bioretention media on nutrient removal (Goh et al. 2015)

Four types of bioretention mixes were investigated for this study. Two of the medias contained types of compost and the other two used shredded newspaper and were enhanced with crushed cockle shell. Results from the study displayed that organic matter content had no effect on nutrient removal which seems inconsistent with other studies. However, the author later describes that bioretention media enhanced with 10% crushed cockle shell removed the most TP up to 95.6%.

3.1.5: Comparison of filter media materials for heavy metal removal from urban stormwater runoff using biofiltration systems (Lim et al. 2015)

This study evaluated the ability of various bioretention filter media to remove heavy metals from stormwater. Coconut coir was one of the materials tested. This study was conducted in Singapore.

The experiment used low and high doses of simulated stormwater. Coconut coir could remove Pb, but it was not able to remove enough Pb in the high dose simulated stormwater to meet the WHO Pb limit. Coconut coir leached total organic carbon (TOC) throughout the experiment at a level of about 10mg/L after 15 doses. The study found that dry periods elevated TOC leaching. Coconut coir was less effective for metal uptake than potting soil, sludge, and compost. Cu removal was particularly low for all materials tested, which has been reported in past studies as well, which is thought to be due to the smaller ionic radius of Cu. Cu leaching was reported for the coconut coir. The use of coconut coir is a sustainable reuse of waste but did not perform as well for heavy metal removal in comparison to potting soil, sludge, and compost. Therefore, coconut coir may be used as an amendment to filter media mixes, but there are better materials that can be used for heavy metal uptake.

Water Treatment Residuals (WTRs)

3.1.6: Alum residuals as a low technology for phosphorus removal from aquaculture processing water (Mortula et al. 2006)

This study evaluated the use of aluminum based water treatment residuals (Al-WTR) for phosphorus removal in water used for aquaculture in the Nova Scotia area of Canada. The effectiveness of Al-WTR for phosphorus removal was evaluated as well as the potential for Al-WTRs removal of organic matter and potential leaching of aluminum from the use of Al-WTR's.

The study found that the use of 4-16g Al-WTR/L water sample of Al-WTR used from Lake Major Water Treatment Plant, Halifax Regional Municipality, Canada effectively removed 94-99% of phosphorus from a water sample containing 2.0mg/L of phosphorus. The study also discussed how the use of Al-WTRs would need to be properly disposed of after the media became saturated because phosphorus leaching could become a problem with saturated media. When investigating the leaching of aluminum from the use of Al-WTR media it was found that the leaching did not exceed 0.5mg Al/L and was deemed non-toxic to aquatic life. The study also found that the use of Al-WTRs was effective at removing organic matter from the sample at a rate of 11g organic matter/kg WTR.

3.1.7: Surface applied water treatment residuals affect bioavailable phosphorus losses in Florida sands (Oladeji et al. 2007)

This study evaluated the use of Al-WTR's to minimize bioavailable active phosphorus (BAP) losses when Al-WTR was coapplied with P-sources (biosolids) in rainfall events.

Al-WTR was coapplied at a rate of 0 g WTR/kg soil and 10 g WTR/kg soil with biosolids with various water extractable P contents (1.2-5.5 g P/kg biosolid). Water extractable P content is the amount of phosphorus that can leach by water flow through on a g of phosphorus per kilogram of soil basis. Phosphorus was applied at a rate of 56 and 224 kg P/ha representing low and high P content soils. 3 rainfall events were applied to media at an intensity of 7.1 cm/ha – representing a 10-year storm event for southern Florida. It was found that the coapplication of Al-WTR with the range of biosolids caused a 46.2-53.7% reduction in BAP leaching. Runoff BAP leaching in the presence of Al-WTR was 24 ± 5 mg, while the leaching without the presence of Al-WTR was 47

± 9 mg. This study concluded that the use of Al-WTR's can be useful for reducing P-losses associated with high influent P concentrations.

3.1.8: Controlled application rate of water treatment residual for agronomic and environmental benefits (Oladeji et al. 2007)

This study aimed to optimize the amount of Al-WTR amended in a soil medium to achieve environmental benefits without negatively affecting plant growth due to unavailable phosphorus in the soil.

Equations were presented in the study that aimed to optimize environmental benefits and plant growth.

$$\text{Eq. [1]. SPSC (mg P/kg)} = (0.15 - \text{PSR})(\text{Al}_{ox} + \text{Fe}_{ox}) \times 31$$

$$\text{Eq. [2]. APSC (mg P/kg)} = ([0.15 - \text{PSR}][\text{Al}_{ox} + \text{Fe}_{ox}]) \times 31$$

$$\text{Eq. [3]. SPSC}_{soil} \times \text{Weight}_{soil} + \text{APSC}_{source} \times \text{Weight}_{source} + \text{APSC}_{WTR} \times \text{Weight}_{WTR}) * (\text{Weight}_{soil} + \text{Weight}_{source} + \text{Weight}_{WTR}) = \text{SPSC}_{expected}$$

Abbreviations: SPSC, soil phosphorus storage capacity PSR, Phosphorus saturation ratio; Al_{ox}, oxalate-extractable aluminum; Fe_{ox}, Oxalate-extractable iron; PSC, phosphorus storage capacity

The study found that to create a situation where plant growth is unaffected and the environmental benefits of a WTR amendment are achieved, a value of soil P storage capacity (SPSC) of 0 is required. Values below 0 SPSC indicate a situation where the environmental benefits of Al-WTR are not being utilized, and a SPSC value above 0 indicates that the Al-WTR is causing P to be immobilized to the extent that there is decreased plant growth/yield. Al-WTR was applied at rates of 0, 10, and 25 g/kg and was coapplied with biosolids ranging from 1.2 g/kg-5.5g/kg of water extractable P content, which is the amount of phosphorus that can leach by water flow through on a g of phosphorus per kilogram of soil basis. Ideal application rates of Al-WTR for plant growth and environmental benefit for this study was found to range between 10-15 g WTR/kg soil.

3.1.9: Use of dewatered alum sludge as a substrate in reed bed treatment systems for wastewater treatment (Zhao et al. 2007)

In this study the use of dewatered aluminum sludge for beneficial phosphorus, COD, BOD_5, and suspended solids (SS) removal in a reed bed was evaluated. This study aimed to investigate the long-term use of Al-WTR's for a cost-effective reuse of waste in water treatment systems. This study was conducted in Dublin, Ireland.

Vertical and horizontal flow systems were investigated. The horizontal flow system is similar to the use of Al-WTR amendments in a rain garden. The aluminum-water treatment sludge was ground and sieved into 1.18-2.36mm particles and then layered into the reed bed at a 10cm depth. The content of the WTR used was 46% Al_2O_3. The concentration of pollutants in the influent were; 34 mg/L phosphorus, 765 mg/L BOD_5, 1150mg/L COD, and 510 mg/L SS. For the first 140 days of operation the use of Al-WTR amendment in the reed bed produced a 90.5% removal of phosphorus, 68.5% removal of BOD_5, 67.1 removal of COD, and 89.5% removal of SS. After the first 140 days of operation the removal efficiencies were 91.8% for phosphorus, 77.7% for BOD_5, 82.1% for COD, and 92.8% for SS. This system showed that an Al-WTR amended reed bed sufficiently removed pollutants for 193 days. The researchers are worried about long term trials showing signs of clogging but this did not occur in the 193-day experiment. If clogging occurs the WTR layer would need to be removed and replaced. Al^{3+} was leached from the reed beds but the levels of release were deemed insignificant. The use of Al-WTR's in the reed bed was much more effective at phosphorus removal than a conventional reed bed and could be an environmentally and economically feasible amendment for bioretention media.

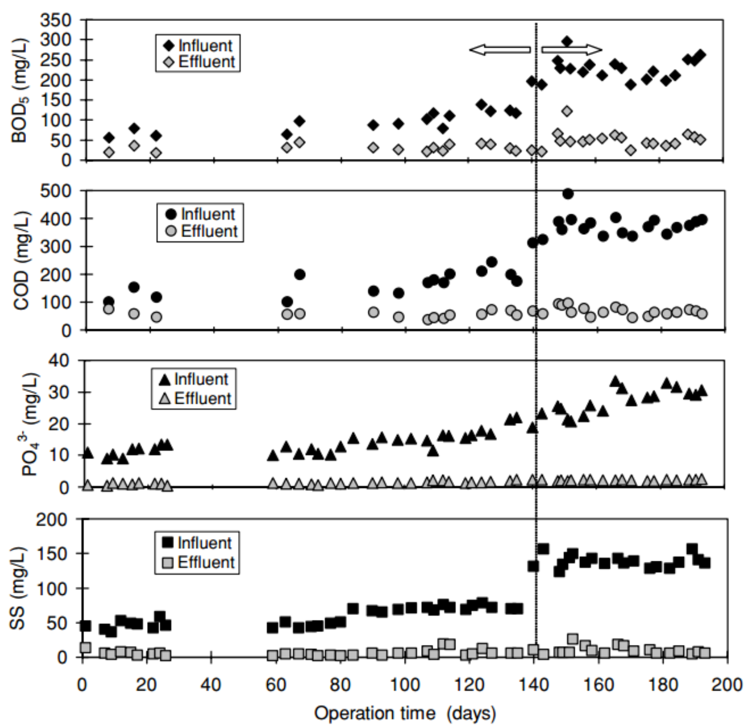

Figure 4 Experimental results of horizontal flow vegetated sludge wetland from Zhao et al. (2007)

3.1.10: Water treatment residuals and biosolids co-applications affect semiarid rangeland phosphorus cycling (Bayley et al. 2008)

This study investigated the effects of co-application of biosolids with WTR's for an extended period, and the effects of a repeated co-application of biosolids with WTR's in the Fort Collins area. The experiment was conducted by R.M. Bayley, and Jim Ippolito an environmental soil quality professor at CSU. The study was conducted at the Meadow Springs Ranch owned by the

City of Fort Collins.

In the study 7.5 by 15m plots were loaded with Al-WTR at a rate of 5, 10, 21 Mg WTR/ha with a biosolid load rate of 10 Mg/ha. The Al-WTR and biosolid amendments were applied in 1991, and reapplied in 2002. The Al-WTR was obtained from the Fort Collins Drinking Water Facility, and the biosolids were obtained from the Fort Collins Wastewater Treatment Facility. The results showed that after 13 years of use the Al-WTR was still acting as the major P-sink. After reapplying the WTR and biosolids amendment the effectiveness of P-removal was not significantly changed. The long-term effectiveness and ability to reapply Al-WTR's for phosphorus removal could prove to be economically beneficial.

3.1.11: Characterization of aluminum-based water treatment residual for potential phosphorus removal in engineered wetlands (Babatunde et al. 2009)

This study investigated the potential reuse of Al-WTR in a constructed wetlands for phosphorus removal and was conducted in Dublin, Ireland.

Performing a column study found that the optimal adsorbent dosage for Al-WTR is 10 g AL-WTR/L which achieved a 95% phosphorus removal after 48 hours for an initial concentration of 5 mg P/L. A dosage of 20 g/L of Al-WTR had a removal rate of 97%. The 2% increase between 10 g/L and 20 g/L was deemed marginal. It was found that the maximum adsorption capacity for the Al-WTR used was 31.9 mg P/g AL-WTR. Other industry by-products used for phosphorus removal have an adsorption capacity range of 0.31-44.2 mg P/g AL-WTR. This indicated that the use of Al-WTR has a similar adsorption capacity to other industry by-products used while also having an effective removal capacity for phosphorus. It was determined that the pH and electrical conductivity of the Al-WTR are reasonable for plant growth. The study also found the removal of P from the WTR application happens quickly as there was not a significant increase in P removal from extending the hydraulic retention time from m 0.125 days to 0.17 days. The study concluded that the use of Al-WTR's as an amendment for constructed wetlands to be a practical and novel idea. The use of Al-WTR's is also seen as a sustainable approach for phosphorus removal because WTR's are typically disposed of in a landfill, and the reuse of the WTRs in a constructed wetland is typically cheaper than the cost of disposal.

3.1.12: A two-prong approach of beneficial reuse of alum sludge in engineered wetland: first experience from Ireland (Zhao et al. 2010)

This study investigated the use of aluminum waste sludge as a substrate in engineered wetlands (EW) to remove nutrients under high nutrient loading rates. This study was conducted in Dublin, Ireland.

The study was aimed to find a better method of removing nutrients from an EW as the typical mix of soil, sand, gravel, and crushed stone has proven to be an insufficient means to remove nutrients from wastewater. The multistage EW had a hydraulic loading rate of 1.27 m^3/m^2*d and an incoming phosphorus concentration of 21.0 ± 2.9 mg/L. The Al-WTR substrate was applied at a depth of ~0.75m. In the field test the removal efficiency for phosphorus was 94.6%, and the main removal was thought to be from the Al-WTR. Removal capacity of phosphorus ranged from 0.025-32 mg P/L. The estimated design life of the EW with the Al-WTR substrate is thought to be 2.5-3.7 years, after which the Al-WTR substrate would need to be removed and reapplied. The study concluded that Al-WTR's would be effective for biofilm development and would be able to in support plant growth. The use of Al-WTR's in EW's could be effective for removing phosphorus from wastewater as well as an economically and environmentally beneficial reuse of waste.

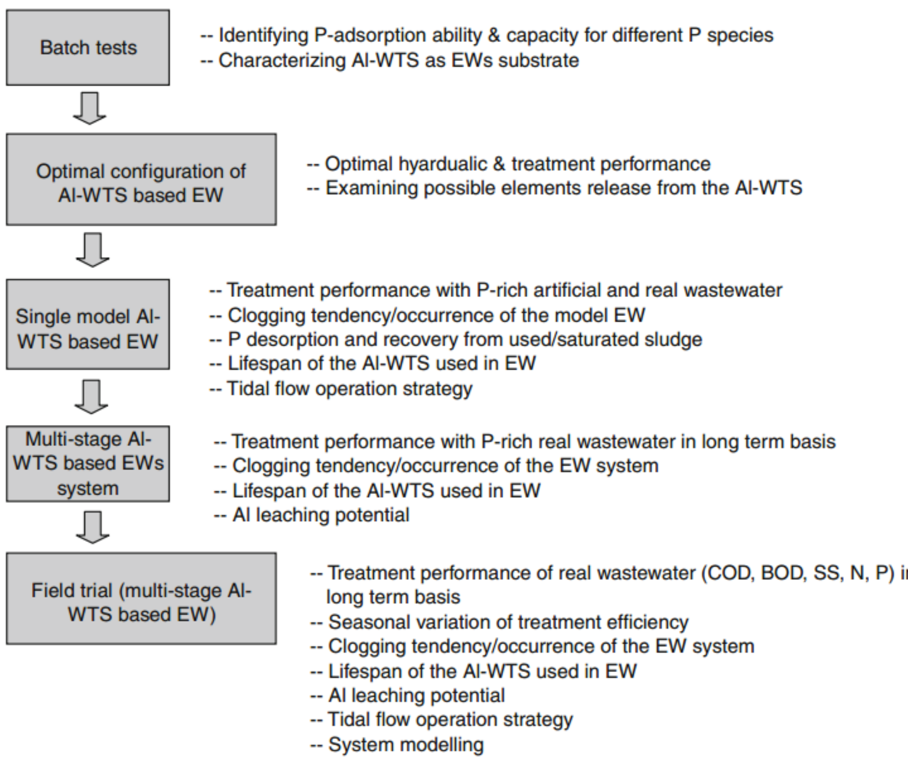

Figure 5 Road Map of the development of the Al-WTS-based Engineered Wetland from Zhao et al. (2010)

3.1.13: Phosphorus removal with by-products in a flow-through setting (Stoner et al. 2012)

This study aimed to investigate the effectiveness of various industrial byproducts for phosphorus removal in a flow through setting. The study also aimed to find a relationship between retention time and phosphorus removal for the industry byproducts. This study was conducted in Oklahoma.

It was found that the phosphorus removal efficiency of byproducts that contain high levels of high-oxalate Al and Fe were not significantly affected by varying retention times. However, byproducts that remove phosphorus by precipitation reactions will remove more phosphorus with longer retention times. In flow through settings, like urban drainage, a material that has high levels of high-oxalate Al and Fe would be a better option for the removal of phosphorus. It was found Al-WTR's can remove 10-50% of phosphorus in flow through settings. Less removal was reported for high initial concentrations of phosphorus. The range of influent phosphorus levels was 0.5, 1, 5, 10, and 15 mg P/L, while the range of retention times was 0.5-10min. The study concluded stating that materials with high levels of oxalate Al, or Fe will be the more effective for phosphorus removal in flow though settings.

3.1.14: Effect of equilibration time on estimates of the maximum phosphorus sorption capacity of industrial by-products using the Langmuir model (Habibiandehkordi et al. 2014)

This study evaluated the maximum phosphorus adsorption capacities of various industrial byproducts (IBP's) based on equilibrium contact time. This study was conducted in Lancaster, United Kingdom.

It was found that the typical 24-hour contact time for equilibrium was too short to estimate total phosphorus adsorption capacity of the IBP's tested and a 5-day contact time was recommended. The IBP's tested were an Al based WTR, Fe based WTR, Fe-lime (CaO) based WTR, and ochre. For the 24 hour contact time maximum phosphorus adsorption was found to be 13.7 mg P/g, 2.4 mg P/g, 9.3 mg P/g, and 10.1 mg P/g for the Al-WTR, Fe-WTR, Fe-lime-WTR, and ochre, respectively. For the 5 day contact time maximum phosphorus adsorption was found to be 28.7 mg P/g, 16.3 mg P/g, 21.4 mg P/g, and 22.2 mg P/g for the Al-WTR, Fe-WTR, Fe-lime-WTR, and ochre, respectively. No further significant adsorption was reported after the 5 day contact time. It is troublesome that a maximum adsorption does not occur until 5 days as this is unrealistic for bioretention cells. However, phosphorus is removed quickly at first and the adsorption rate slows over time. Design life of a phosphorus adsorbing materials depends on the adsorption capacity of the material used. The adsorption capacity of WTR's ranges widely so it is recommended to screen a particular WTR for adsorption capacity before it is used as a phosphorus removing amendment in a bioretention cell.

3.1.15: Influence of the inherent properties of drinking water treatment residuals on their phosphorus adsorption capacities (Bai et al. 2014)

This study investigated the adsorption and desorption of phosphorus in five different WTR's. This study was conducted in Beijing, China.

The different types of WTR's used include; BJ1-WTR and BJ2-WTR, which used a combination of $FeCL_3$ and polymeric aluminum (PAC) and active carbon during water treatment, HZ-WTR and LZ-WTR, in which PAC was used as a coagulant, SD-WTR, in which PAC was used as a coagulant as well as $Ca(HCO_3)_2$ as a softening agent. All samples were dried and sieved to create a homogenous mixture. Influent concentrations of phosphorus were 50 mg/L and 100 mg/L at a pH of 5. The phosphorus removal effectiveness of the WTR's and 50 mg P/L influent were 99% for BJ2-WTR, 99% for HZ-WTR, 88% for BJ1-WTR, 77% for SD-WTR, and 74% for LZ-WTR. The maximum adsorption capabilities of the WTR's ranged from 5.01-9.14 mg P/g WTR at a pH of 5. When the WTR's became saturated with P, desorption of P increased slightly but desorption levels were seen to have a low risk release of P. It was also found that adsorption of P increases as pH decreases which is consistent across most studies. It was found that WTR's with high levels of Al_{ox}, Fe_{ox}, organic matter, and large surface areas would provide the greatest P adsorption. It was also found that WTR's with higher levels of Al_{ox} and Fe_{ox} are thought to present lower levels of desorption when saturated by P.

Table 4 General physicochemical properties of the five drinking water treatment residuals (WTRs) from Bai et al. (2014)

Properties	BJ1-WTRs	BJ2-WTRs	HZ-WTRs	LZ-WTRs	SD-WTRs
Fe (mg/g)	80.10	97.10	28.13	39.54	25.60
Al (mg/g)	42.20	74.25	94.48	49.79	47.27
Ca (mg/g)	8.21	16.54	4.87	49.65	129.83
C (mg/g)	107.74	106.33	41.41	28.77	62.54
P (mg/g)	1.41	1.31	2.86	1.21	1.91
OM (mg/g)	65.72	68.24	40.50	26.25	44.41
Fe_{ox1} (mg/g)	58.80	82.00	8.90	5.70	6.16
Al_{ox1} (mg/g)	39.69	62.00	70.00	18.00	26.73
P_{ox1} (mg/g)	0.34	0.19	2.29	0.61	0.81
PSI (%)	0.44	0.16	2.69	2.57	2.36
Fe_{ox2} (mg/g)	0.11	0.02	0.05	0.01	0.01
Al_{ox2} (mg/g)	0.33	0.03	0.46	0.04	0.03
P_{ox2} (mg/g)	0.01	0.01	0.01	0.01	0.01
Ca_M (mg/g)	7.55	14.03	3.76	40.28	40.01
EC (ms/cm)	0.74	1.25	0.73	0.72	0.50
Surface area (m^2/g)	74	61	52	34	21
pH	7.23	7.30	7.40	7.90	7.60

BJ1-WTRs: samples collected from Beijing in 2011; BJ2-WTRs: samples collected from Beijing in 2012; HZ-WTRs: samples collected from Hangzhou; LZ-WTRs: samples collected from Lanzhou; SD-WTRs: samples collected from Shandong; OM: organic matter; PSI: phosphorus saturation index; EC: electrical conductivity; ox1: 200 mmol/L oxalate extractant; ox2: 5 mmol/L oxalate extractant; M: Mehlich 3 extractant.

3.1.16: Phosphorus speciation and treatment using enhanced phosphorus removal bioretention (Liu and Davis 2014)

Field research conducted at the University of Maryland investigated the water quality performance of a bioretention cell amended with 5% by mass WTR for phosphorus removal. From the study it was found that adding WTR to the bioretention mix provided a 55.1% reduction in TP while simultaneously preventing leaching of dissolved phosphorus from the organic matter. In the study, phosphorus species were split into particulate and dissolved and removal efficiencies were measured for each. From the research it was found that particulate phosphorus removal was unchanged by the addition of WTR, however, the export of dissolved phosphorus was prevented by applying WTR due to the enhanced sorption capacity of the WTR.

3.1.17: Reuse of drinking water treatment residuals as a substrate in constructed wetlands for sewage tertiary treatment (Bai et al. 2014)

This study investigated the use of WTR substrates in constructed wetlands for pollutant and nutrient removal at a range of hydraulic retention times. Both constant flow and tidal flow scenarios were tested. This study was conducted in Beijing, China.

An Al-Fe-WTR from Beijing No. 9 water works was tested. A Plexiglas column of 9.3cm diameter and 90cm depth with 10cm of gravel on bottom and 60cm of WTR (1.2kg), with common reeds planted on top was used for testing. Phosphorus was loaded at a rate of 0.18g/m^3, and a removal efficiency of 98% was recorded after 260 days. The maximum P adsorption capacity was calculated to be 7.42 mg P/g WTR. It is estimated that the WTR would not become saturated by P for over 10 years at the loading rate used. The WTR substrate was also effective at removing total nitrogen, suspended solids, and chemical oxygen demand. Hydraulic retention times did not affect phosphorus removal much, but did affect total nitrogen removal. Longer retention times created greater removal of total nitrogen. The WTR preformed equally as well in both constant flow and tidal flow conditions. The study also investigated the potential of Al or Fe leaching from the WTR and the results showed a low risk for leaching.

3.1.18: Water treatment residues as accumulators of oxoanions in soil. Sorption of arsenate and phosphate anions from an aqueous solution (Castaldi et al. 2014)

This study evaluated Al-WTR's, and Fe-WTR's effectiveness for removing arsenate, and phosphates at a range of pH values from 4.0-9.0. This study was conducted in Sassari, Italy.

It was found that removal efficiencies were similar, but the Fe-WTR removed a higher percentage of phosphates and arsenate than Al-WTR. The removal efficiency for both WTR's was found to be about 50% for phosphates and 65% for arsenate at a pH of 4.0. 1 g of WTR was used per 25ml of a 3mmol solution containing either $Na_2HAsO_4 \cdot 7H_2O$ or $NaH_2PO_4 \cdot 7H_2O$. It was also found that both WTR's preformed best at 4.0 pH, and had decreasing effectiveness as the pH rose. It is thought that the Fe-WTR was more effective because of a larger specific surface area and a greater content of manganese. The study concluded stating that the use of WTR's need to be investigated for heavy metal release, and uptake of Al and Fe in plants to understand the environmental impact of their use.

3.1.19: Aluminum-based water treatment residual use in a constructed wetland for capturing urban runoff phosphorus: column study (Ippolito et al. 2015)

This study evaluated AL-WTR application rates to achieve long-term phosphorus removal in an engineered wetland (EW) for the watershed of Boise, ID.

The four application rates studied were 0, 62, 124, and 264 Mg/ha. It was thought that these application rates would correspond to 0, 10, 20, and 40 year design life's for the phosphorus removal of the EW. However, 0 and 62 Mg/ha were found to be insufficient application rates because they would reduce phosphorus storage capacity and allow soluble phosphorus to move through the system. A 0.19 mg/L concentration of phosphorus was applied to the system and the storage capacity of the Al-WTR was found to be 2.343 mg P/g. The Al-WTR was applied to the top layer of the EW, and would need to be removed and reapplied when the Al-WTR became saturated with P. In the study the Al-WTR maintained its original storage capacity after 14 simulated rainfalls. The study indicates that the higher levels of Al-WTR application rates would be ideal for capturing phosphorus from urban runoff while maintaining plant life. The use of Al-WTR applied to EW's could be an environmentally and economically beneficial reuse of WTR's.

In this study, Al-WTR applied at 6.2 Mg/ha would require 1.86 Mg or about 2 tons of Al-WTR to remove phosphorus from approximately 25 cm of rainfall.

3.1.20: Can industrial by-products enhance phosphorus retention within vegetated buffer strips? (Habibiandehkordi et al. 2015)

This study evaluated the effectiveness of using industrial byproducts (IBP's) with vegetated buffer strips (VBS) as a cost-effective method for removing phosphorus from surface and subsurface flows. This study was conducted in Lancaster, United Kingdom.

The IBP's studied were Al-WTR's, iron ochre, and a control VBS with no surface amendment. The IBP's were applied at a rate of 20 metric tons/ha. Two runoff scenarios were tested, one with high P concentration and one with low. The corresponding total phosphorus concentrations were 4.2 mg/L for the high P concentration and 2.7 mg/L for the low P concentration. For the large P concentration runoff events the removal percentages for the buffer strip with ochre, buffer strip with Al-WTR, and just the buffer strip were 39.6-40.5%, 66.7-68.4%, and 36.6-41.8%, respectively. For the small P concentration runoff events the removal percentages for the buffer strip with ochre, buffer strip with Al-WTR, and just the buffer strip were 54.4-55.3%, 65.6-66.6%, and 53.6-55.9%, respectively.

3.1.21: Water treatment residual (WTR)-coated wood mulch for alleviation of toxic metals and phosphorus from polluted urban stormwater runoff (Soleimanifar et al. 2016)

This study evaluated the effectiveness use of Al-WTR coated mulch for stormwater contaminant removal. This study was conducted in New Jersey.

Al-WTR with 5.6% Al by mass was sieved through a 2mm sieve and ground into a powder. The ground Al-WTR was then glued to a washed mulch of the size 1cm by 2cm. A mass ratio of 1:3 WTR:mulch was used. In the system, there was approximately 10g/L of WTR applied in the artificial stormwater runoff. The artificial stormwater contained initial concentrations of Pb = 100µg/L, Zn = 800µg/L, Cu = 100µg/L, and P = 2.3mg/L. After 120 minutes the filter media adsorbed 97% Pb, 76% Zn, 81% Cu, and 97% P. An adsorption capacity of 0.22 mg P/g for the Al-WTR coated mulch was found. Leaching of contaminates from the tests were all within U.S. criteria and was found to not be an issue. Using Al-WTR mulch could alleviate infiltration problems with the use of Al-WTR amended filter media. The use of Al-WTR coated mulch proved to be effective at removing metals, and phosphorus from stormwater while not being an issue for toxic contaminant leaching which shows its use as a cost-effective bioretention media to handle non-point pollutant loads.

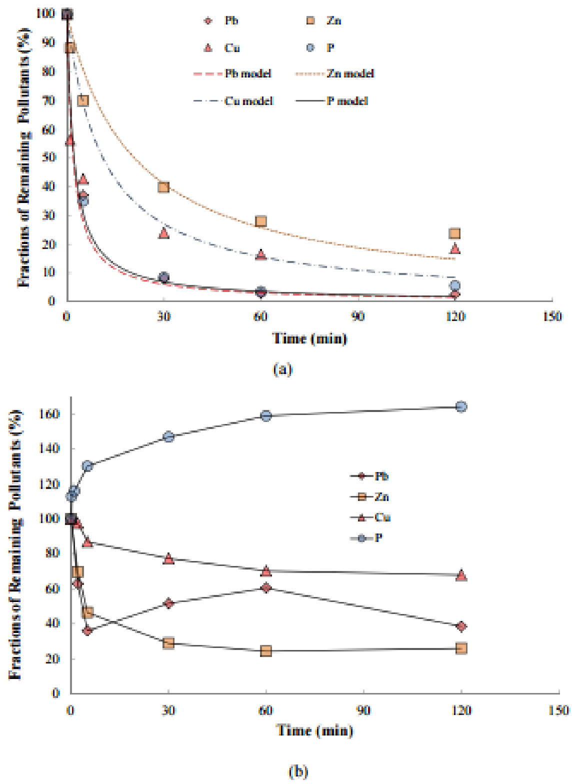

Figure 6 Fractions or remaining pollutants with time during the mulch adsorption of Pb, Zn, Cu, and P in a synthetic polluted water (batch tests): (a) WTR-coated wood mulch; and (b) uncoated wood mulch (control) (WTR = 10g/L; pH = 7.0; initial concentrations: Cu = 100 µg/L, Zn = 800 µg/L , Pb = 100 µg/L, and TP = 2.30 mg/L; relative standard deviations were less than 6.0%, not shown in figure). from Soleimanifar et al. (2016)

3.1.22: Evaluation of natural organic matter release from alum sludge reuse in wastewater treatment and its role in P adsorption (Liu et al. 2016)

This study evaluated natural organic matter (NOM) release from aluminum sludge to better understand the risk of using aluminum based byproducts to treat stormwater. Although NOM is not toxic, the byproducts of NOM release, disinfection byproducts (DBP's), can be toxic and pose a risk to human and environmental health. This study was conducted in Dublin, Ireland.

Overall the study found NOM leakage to not be a big concern with an average release of 2.76-7.57 mg/L for the column tests, and 0.51-4.26 mg/L of release for the batch reactor test. Total phosphorus removal for the column test was 75-99% and 99% for the batch reactor test. NOM release was positively correlated to initial pH, and P adsorption. The risk associated with NOM release using aluminum sludge amendments to bioretention media is seen to be minimal from this study. The study also addressed Al^{3+} release from the use of aluminum sludge amendments in a constructed wetland and stated that in a previous study Al release ranged from 0.02-0.06 mg/L in a field scale reactor. This Al leaching rate is still within drinking water standards. This study aimed to assess the risk of aluminum sludge use as bioretention media and found that it should not cause risk due to NOM, or Al leaching, but stated that there is a lack of analysis on the potential toxicity of WTR's for their use in stormwater management and further research needs to be done to confirm their safety. The study also stated that every WTR will have different physical and chemical properties and those properties should be studied before practical use.

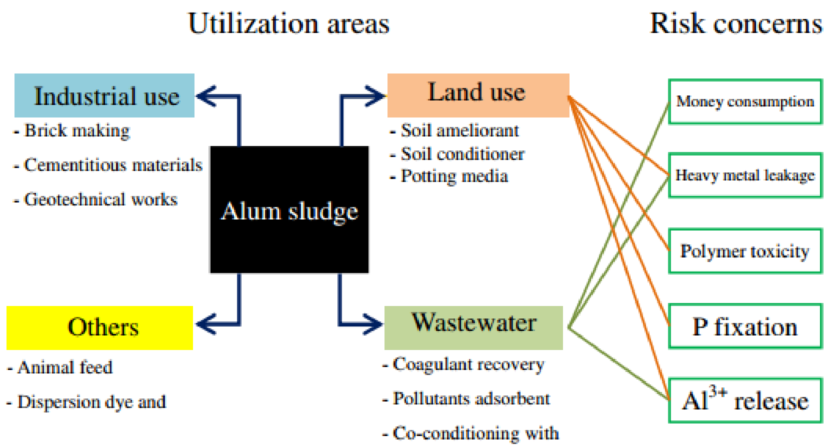

Figure 7 Reuse and utilization of alum sludge with corresponding concerns

Biochar

3.1.23: Evaluation of biochar as a potential filter media for the removal of mixed contaminants from urban storm water runoff (Reddy et al. 2014)

This study evaluated the effectiveness of biochar as filter media for pollutant removal from a simulated storm water. This study was conducted in Illinois.

The study was a column test in which biochar was created by a gasification process at 520ºC using waste wood pellets as feedstock. The biochar was sieved through a 4.75mm sieve then sieved again through a 2mm sieve, and the material left on the 2mm sieve was used for the tests. This created a mean particle size of 3.2mm. The targeted pollutants for removal were total suspended solids (TSS), nitrate, phosphate, heavy metals, polyaromatic hydrocarbons (PAH's), and *E. coli*. The removal efficiency of the media for different pollutants is outlined in Table 6. There was no leaching of phosphate from flushing the biochar material. Biochar has the potential to be a useful amendment for bioretention filter media, but further studies need to be conducted to find an effective type of biochar to use, and a type of filter media it would work best with. The removal of phosphates from the use of biochar is much lower than for water treatment residuals which is thought to be a result of the overall negative charge for the biochar constituents compared to the overall positive charge of the water treatment residuals constituents.

Table 5: Removal Efficiencies for the use of Biochar as Filter Media

Targeted Pollutant	Influent Concentration	Percentage Removal

TSS	145-150 mg/L	86
Nitrate	5-15 mg/L	86
Phosphate	0.5-1 mg/L	47
Cd	20-30 mg/L	18
Cr	1-5 mg/L	19
Cu	1-5 mg/L	65
Pb	0.5-5 mg/L	75
Ni	100-120 mg/L	17
Zn	50-60 mg/L	24
PAH's	10-700 µg/L	68
E. coli	3,500-8,200 MPN/100 mL	27

3.1.24: Phosphorus removal from secondary sewage and septage using sand media amended with biochar in constructed wetland mesocosms (Rozari, 2016)

This study evaluated the use of sand amended with biochar as a phosphorus removal technique in vertical flow constructed wetlands. The study aimed to achieve natural environmental conditions in a lab setting by using actual secondary treated wastewater and raw septage. This study was conducted in South East Queensland.

Sand was amended with biochar in a range of 0 to 25% biochar by volume. 21 vertical flow mesocosm bins measuring 0.5m by 0.5m by 0.98m planted with one Melaleuca tree and one lemongrass plant were each subject to a continuous flow of either secondary treated wastewater or raw septage. TP and PO_4-P loadings varied based on the time frame but ranged from 0.04-0.26 mg/d, and 0.03-0.22 mg/d, respectively. TP and PO_4-P removal for the secondary treated water were 42-91%, and 43-92%, respectively. TP and PO_4-P removal for the raw septage were 30-83%, and 35-85%, respectively. It was found that as the percentage of biochar amended in the sand increased the rate of phosphorus removal decreased. Although the biochar amended sand performed better for BOD_5, TSS, TN, NH_4-N, NOx, and coliform removal it preformed worse for phosphorus removal. The use of biochar amended sands also related to less biomass in the vegetation in the mesocosm. This study concluded saying that the use of biochar, especially different types of biochar, as amendment media for pollutant removal needs to be further researched.

3.1.25: Effects of submerged zone, media aging, and antecedent dry period on the performance of biochar-amended biofilters in removing fecal indicators and nutrients from natural stormwater (Afrooz et al. 2017)

This study evaluated the effects of dry periods, and presence of a saturation zone on the effectiveness of a biochar amended bio filter to remove fecal indicators and nutrients from natural stormwater.

A biochar amended bio filter was created with Ottawa sand 0.6-0.8mm particle size and biochar at a ratio of 7:3 by volume. The biochar used was crushed to sizes of <0.6mm, and was constituted of 60% Monterey Pine, 20% Eucalyptus, 10% Bay Laurel, 10% mixed hardwood and softwood. The concentration of pollutant varied as natural stormwater was used for the study. There were three scenarios that include the use of an unsaturated zone biofilter with biochar that had stormwater applied every 3 days, an unsaturated zone biofilter with biochar that had stormwater applied every 7 days, and a saturated zone biofilter with biochar that had stormwater applied every 7 days. Results for nutrient removal are as follows.

Unsaturated zone biofilter with biochar – with stormwater application every 3 days

- Removal of NH_4^+-N – 50-58%
- TN removal - 19.0 ± 8.5%
- TP removal - 21.9 ± 14.5%

Unsaturated zone biofilter with biochar – with stormwater application every 7 days

- Removal of NO_3^- 36.1 ± 6.9%
- Removal of NH_4^+-N – 50-58%
- TP removal - 18.8 ± 10.7%

Saturated zone biofilter with biochar – with stormwater application every 7 days

- Removal of NO_3^- 61.4 ± 3.4%
- Removal of NH_4^+-N – 50-58%
- TN removal - 26.8 ± 7.2%
- TP removal - 19.7 ± 6.9%

Over time the biofilters showed no change in total phosphorus removal, a greater removal of total nitrogen and a decrease in fecal indicator removal. There was no significant change in hydraulic conductivity of the 20-week test showing that infiltration rates did not reduce. The biochar filters did not provide adequate phosphorus removal, and leached dissolved organic carbon during their use. The poor phosphorus removal could be due to the properties of the biochar. Therefore, other mixtures of biochar should be researched to understand their potential for phosphorus removal.

3.1.26: Improved contaminant removal in vegetated stormwater biofilters amended with biochar (Ulrich et al. 2017)

Use of biochar is a growing media option for providing additional sorption capacity within bioretention media mixes. Biochar is made up of carbonaceous sorbents that are added to bioretention media mixes to replace granular activated carbon. This study evaluated sand filters and biofilters with biochar, granular activated carbon, and unamended column types. From the study, it was seen that biochar-amended sand filter and biofilters both showed increases in removal for total organic carbon (TOC), nutrients, metals, and E. Coli.

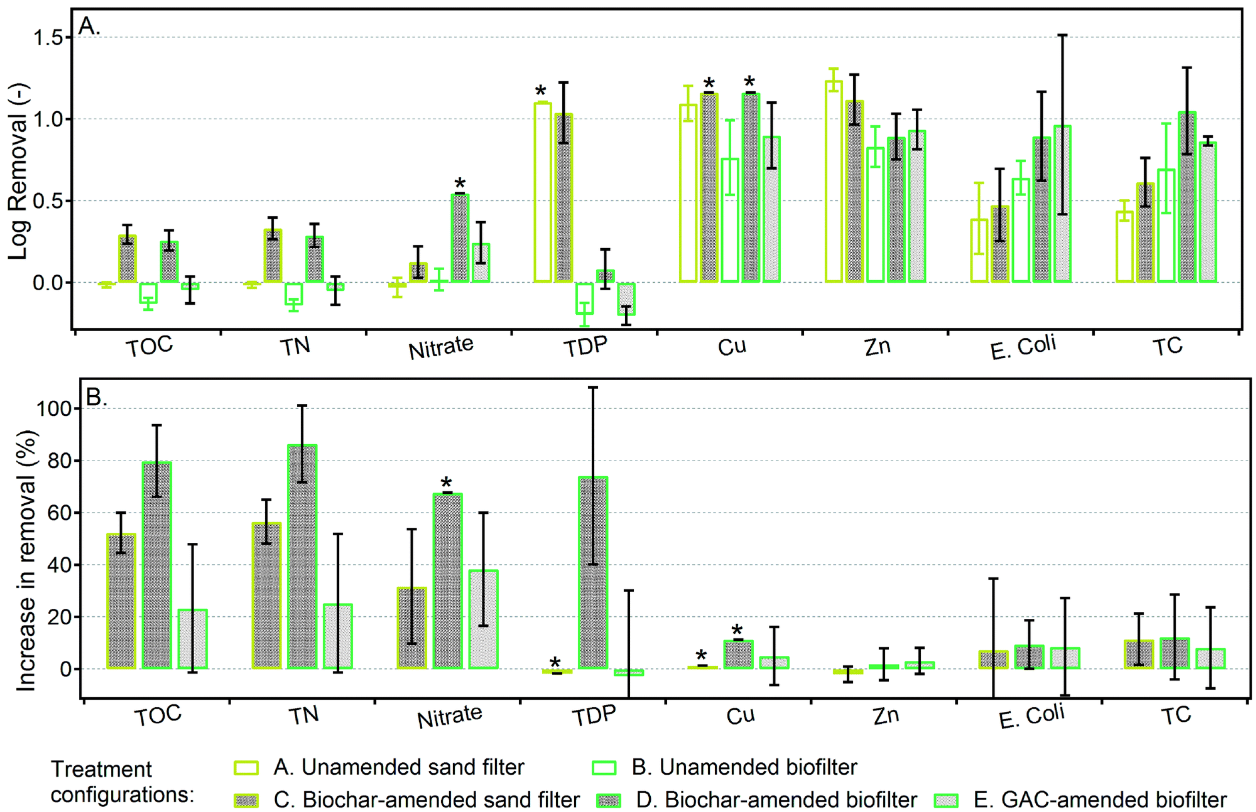

Figure 8: (A) Log removal (-log[$C_{effluent}/C_{influent}$]) for TOC, nutrients, metals, and indicator bacteria among the treatment configurations during the final high-volume dosing experiment (a negative log removal represents a load increase in the effluent). Asterisks indicates cases where effluent contaminant concentrations were below detection limits. (B) Percent increase in contaminant removal due to sorbent amendment (i.e., percent removal in sorbent-amended configurations, minus the percent removal in unamended configurations).

Industry By-Products

3.1.27: PO_4^{3-} removal by and permeability of industrial by-products and minerals: granulated blast furnace slag, cement kiln dust, coconut shell activated carbon, silica sand, and zeolite (Agrawal et al. 2011)

This study investigated the ability of granulated blast furnace slag (GBFS), cement kiln dust (CDK), zeolite sand, silica sand, and coconut shell activated carbon (CS-AS) to remove phosphates from wastewater while maintaining a hydraulic conductivity of at least 0.001 cm/s.

The study found that for influent phosphate concentrations of 0, 3, 7, 18, 43, or 68 mg/L of PO_4^{3-} GBFS and a ratio of 5:95% CDK/sand blend had the potential to remove >98% of phosphates, CS-AS could remove 70-79% phosphates, and zeolite and silica sand could remove 21-58% of phosphates. All of the tested materials maintained a hydraulic conductivity of 0.001 cm/s throughout the tests. However, a ratio of 10:90% CDK became unable to maintain a hydraulic conductivity of 0.001 cm/s throughout the 24-hour testing period. The main method of removal was thought to be from precipitation and adsorption. The materials containing higher levels of

Al, Fe, and Ca were more effective at removing phosphates. More research must be done to better understand the practical use of these materials in full scale systems to quantify their effectiveness in the field and to predict their design life. The study concluded by stating that the industry byproducts tested proved to be capable of removing phosphates from agricultural effluents while maintaining a sufficient hydraulic conductivity and could reduce the waste generated from various industries.

3.1.28: Use of phosphorus-sorbing materials to remove phosphate from greenhouse wastewater. (Dunets et al. 2015)

This study evaluated the effectiveness of basic oxygen furnace slag (BOS), and a concrete waste material (CW) in removing phosphorus from a simulated greenhouse wastewater. This study was conducted in Ontario, Canada.

Both the BOS and CW were mixed 40/60 material to sand and were not sieved before experimentation. Both materials tested were dosed with either 20 or 60 mg P/L and effectively removed >99% of phosphorus with a 3-hour hydraulic retention time. For a 3 hour hydraulic retention time the BOS and CW had phosphate retention capacities 8.8 and 5.1 mg P/g, respectively. The phosphate retention capacity of BOS was increased to >10.5 mg P/g when the hydraulic retention time was increased to 24 hours. Both materials contained high levels of Ca, which is thought to be the main component of phosphorus removal for the materials. It was found that a higher pH, typically higher than a pH of 9, will be most effective for materials that use Ca to remove phosphorus. Although both materials removed phosphorus effectively, BOS would be a better choice for bioretention filter media as BOS has a greater phosphate retention capacity giving it a longer design life. The study also ended saying that the P saturated filter media could potentially be used as a fertilizer.

3.1 Secondary Sources

The secondary sources are sources that referenced other primary sources for the effectiveness of many different bioretention media for phosphorus removal. The information gathered in secondary sources reflects an evaluation of a wide variety of bioretention media and how to apply bioretention media effectively.

3.2.1: Drinking water treatment residuals: A review of recent uses (Ippolito et al. 2011)

This study evaluated the characteristics of WTR’s, described how P sorption occurs with WTR’s, potential uses of certain WTR’s to remove other contaminants from water sources, the effect WTRs have on microfauna, insects, and animals, the environmental impact of WTR’s used in soil, and to see how radioactivity accumulates in WTRs.

From a variety of past studies, it was found that WTRs can retain 1,740 to 37,000 mg P/kg and the phosphorus retained will not easily leach. One of the promising aspects of WTR use for phosphorus removal is that the phosphorus is removed very quickly. It was found that about 50% of phosphorus will be removed in 2 minutes, 90% in 15 minutes, and nearly 100% in 24 hours of contact time. Studies have also found WTR’s to be a long-term P sink. For example, a study

Bayley et al, (2008), a study that used Fort Collins Drinking Water Facilities’ Al-WTR, found the Al-WTR to be acting as a major inorganic P-sink 13 years after applying Al-WTR with a biosolid. A study, Agyin-Birkorang et al. (2007), found a 60% reduction of total phosphorus in runoff and leachate 7.5 years after application. WTRs have the potential to be a long-term P sink, and are economical which promotes their use for the treatment of urban stormwater. This study also outlines the potential negative effects of WTR application as well, which include the ability to immobilize plant available P which could cause P deficiencies in plants, the potential for Mn or Na toxicities for sensitive crops, and the potential for radioactivity to accumulate in WTR which is based on the minerals in contact with the source of the WTR.

Table 6: Positive and negative attributes of water treatment residuals from Ippolito et al. (2011)

Positive WTR† attributes	Negative WTR attributes
a. Increases soil P sorption capacity in P-enriched soils.	a. Can adsorb P in P-poor soils, leading to plant P deficiencies.
b. Sorbs P in high P-containing materials such as poultry litter, other manures, biosolids, waters.	b. May contain excess Mn or Na, which may be detrimental to sensitive plant species.
c. Sorbs As(III/V) Se(IV/VI), ClO_4^-, Hg, heavy metals.	c. May contain radionuclides depending on geologic materials in contact with source water.
d. May be used as a best management practice in nutrient sensitive ecosystems.	d. May be expensive to landfill depending on hauling costs, tipping fees, etc.

† WTR, water treatment residual.

10 Journal of Environmental Quality • Volume 40 • January–February 2011

3.2.2: Filter materials for phosphorus removal from wastewater in treatment wetlands—A review (Vohla et al. 2011)

This study evaluated the effectiveness of a wide variety of materials for phosphorus removal. The list of materials and their effectiveness is split into three categories; natural materials, industry-by products, and manmade products. The list of materials studied in this research is extensive and the summary will only include materials deemed to be notable for phosphorus removal.

The notable natural materials include activated bauxite, laterite, maerl, polonite, and wollastonite which removed >95%, 96%, 98%, 96.7%, 51.1-93% of phosphorus, respectively. The adsorption capacities of these materials are 2.95 mg P/g, 0.034-7.49 mg P/g, 0.1-12,000 mg P/g for activated bauxite (>$1000 per ton), maerl, and wollastonite ($205-$345 per ton) respectively. No P adsorption capacity information was given for laterite, or polonite. P removal reported for these materials are high, but P adsorption capacity varies greatly and could be an issue for long term use of materials as bioretention filter media.

The notable industrial byproducts include fly ash, ochre, basic oxygen furnace slag, and blast furnace slag which removed 83%, 90%, 90.4%, 85.6-95% of phosphorus. The adsorption capacities of these materials are 0.081-29.5 mg P/g, 0.026 mg P/g, 9.15 mg P/g for fly ash, ochre, and blast furnace slag, respectively. No information was given regarding the P adsorption of basic oxygen furnace slag.

The notable man made products include Filtralite P™, LWA, and LECA which removed 99.3%, 88%, and 90% of phosphorus, respectively. The adsorption capacities of these materials are 3.2 mg P/g, and 4 mg P/g for LWA, and LECA, respectively. The use of these man made materials may not be practical as they cost more to obtain than other equally as effective materials.

3.2.3: Engineered infiltration systems for urban stormwater reclamation (Grebel et al. 2013)

This study evaluated many other studies in the aim of optimizing treatment of stormwater by the manipulation of media materials, hydraulic retention times, and redox reactions.

There are many amendments that can target phosphorus removal which include Al or Fe-coated sand, fly ash, shale, cementious media, and limestone and of these materials Al-oxide media is thought to be the most effective amendment for phosphorus removal. The study also states that increased hydraulic retention times can aid in pollutant removal in a bioretention cell. However, with an increased hydraulic retention time the volume of the cell must be greater, which in turn raises capital costs. The article notes how design life of a bioretention cell can vary depending the type of media used and the pollutant load from stormwater varying over time.

This study addresses the fact that creating a more efficient bioretention cell should be seen from a systematic approach. Bioretention media with different amendments could be layered to minimize pollutant leaching. For example, a layer of Al-WTR coated sand could be below a compost layer to minimize nutrient leaching. The compost layer being on top would be beneficial for metal reduction, but would leach phosphorus, this leached phosphorus could then be retained by the Al-WTR coated sand. There are positives and negatives to using specific amendments in bioretention media and the take home is that no one single amendment is going to remove all the pollutants from stormwater, but the use specific amendments in a logical layered order could improve the effectiveness of bioretention cells greatly.

3.2.4: Review of dissolved pollutants in urban storm water and their removal and fate in bioretention cells (LeFerve et al. 2014)

This study evaluated how bioretention media removes dissolved nutrients, toxic metals, and organic compounds from stormwater. This study also discusses the sources of dissolved pollutant loads in bioretention cells. Removing dissolved nutrients using bioretention media has not be extremely successful, but this study has recommendations on how to achieve nutrient removal while maintaining the other positive aspects of the bioretention cell. When targeting phosphorus iron, fly ash, or WTR amended sand is suggested. Typically, in bioretention cells there is a layer with compost or organic matter, used for heavy metal removal but this layer can leach nutrients. It is suggested that the first layer of the cell should be high in organic matter followed by nutrient removing layers to remove leached nutrients.

Table 7 shows the removal efficiencies of various bioretention media discussed in the study. Figure 9 is a schematic that shows the authors design recommendation for a bioretention cell that removes dissolved metals, nitrogen, phosphorus, suspended solids, and hydrophobic organic compounds.

Table 7: Removal Effectiveness and of Various Bioretention Media (LeFerve et al. 2014)

Material	Phosphorus Removal
Chopped steel-wool amended soil	81%
Steel-wool fabric-amended sand	47%
Iron enriched sand	88%
Iron enhanced filtration trenches	71%
Dougherty sand with fly ash (2.5%)	66%
Dougherty sand with fly ash (5%)	85%
WTR amended mesocosm	95-99%
Mixture: loamy sand, 5% WTR, 3% shredded bark	89%
Vegetated sand and loam mesocosm	90-100%
Sandy loam planted with native plants	90%

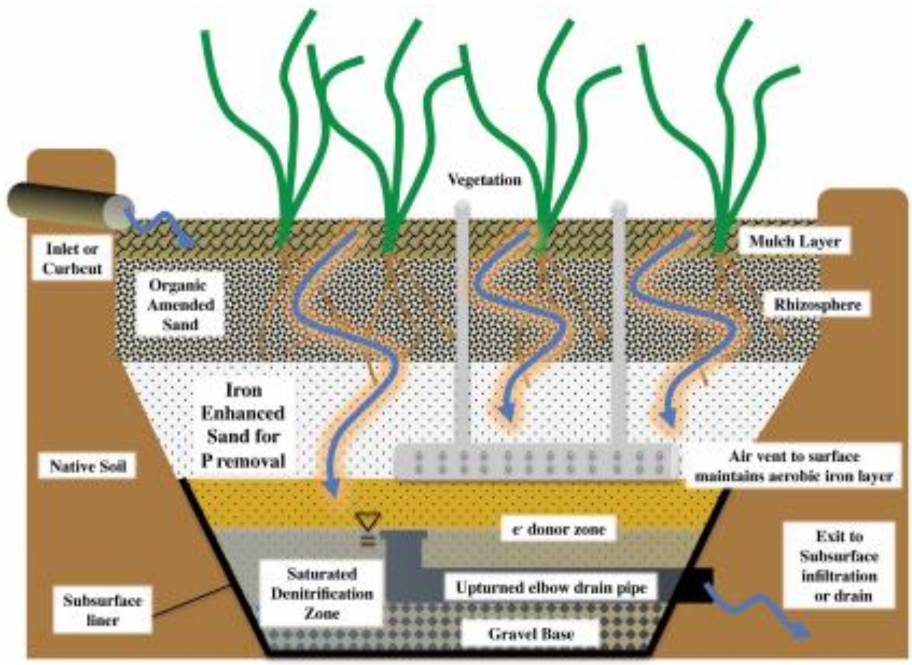

Figure 9: Schematic diagram of a three-stage bioretention cell incorporating a top layer of organic-amended sand for capture of suspended solids, dissolved metals, and hydrophobic organic compounds, and iron-enhanced sand middle layer to capture phosphate as proposed in Erickson et al. 2011, and a saturated anoxic zone with e-donor to promote denitrification; an upturned elbow drainpipe creates an internal water storage zone to promote saturated or anoxic conditions from LeFerve et al. (2014)

3.2.5: Review of dissolved pollutants in urban storm water and their removal and fate in bioretention cells (LeFevre et al. 2015)

An extensive review was conducted for the effectiveness of bioretention cells and the removal of dissolved pollutants. The paper discusses the importance of bioretention cells and how their effectiveness has been quantified for the treatment of urban stormwater. After discussing the need for bioretention cells, the authors describe the importance of dissolved pollutants and how the traditional filtering capacity is not very effective at removing dissolved pollutants. Studies which evaluated the removal of nitrates, nitrite, orthophosphate, dissolved-P were included in the review. Types of medias that were evaluated included traditional mix with sand and compost/mulch, shredded paper, WTRs, red mud, and industrial by-products. Removal of each media type varied among studies, but for phosphorus, WTRs consistently outperformed other materials in both effectiveness and consistency.

3.2.6: A unified look at phosphorus treatment using bioretention (Li et al. 2016)

This study evaluated the use of different types of bioretention media used to remove phosphorus.

The author notes how typical bioretention media used (e.g. sand/compost/mulch) has shown to be variable in phosphorus removal. The use of WTR amended sands or soils could create less uncertainty in the ability of bioretention media to remove phosphorus. The study found the optimal amount of WTR to be added to bioretention media to be 5% by weight. In this optimal media hardwood bark was used as well to increase infiltration rates. However, if vegetation is to be grown in the media the amount of WTR applied may need to be modified to support plant life. The authors found that media with high levels of P adsorption capacity could last up to 20-30 year before they become completely saturated. This 20-30 years is the time until there is no phosphorus removal occurring by the media anymore, the media may become less effective over time before this point as well. The study concludes saying that the use of WTR, steel slag, Fe or other P-adsorbing materials will create less uncertainty in design, and designing a bioretention media with these materials could drive effluent phosphorus concentrations to zero.

4.0: References

Afrooz, A.R.M Nabiul., Boehm Alexandria B. (2017) "Effects of submerged zone, media aging, and antecedent dry period on the performance of biochar-amended biofilters in removing fecal indicators and nutrients from natural stormwater" Ecological Engineering 102, 320-330.

Agrawal, Sheela G., King, Kevin W., Fischer, Eric N., Woner, Dedra N. (2011) "PO4 3− Removal by and Permeability of Industrial Byproducts and Minerals: Granulated Blast Furnace Slag, Cement Kiln Dust, Coconut Shell Activated Carbon, Silica Sand, and Zeolite" Water Air & Soil Pollution 219, 91-101.

Agyin-Birikorang, S., O'Connor, G.A. (2008). "Evaluating Phosphorus Loss from a Florida Spodosol as Affected by Phosphorus-Source Application Methods" J. Environ. Qual. 37, 1180–1189. doi:10.2134/jeq2007.0535

Babatunde, A.O., Zhao, Y.Q., Burke, A.M., Morris, M.A., Hanrahan, J.P. (2009). "Characterization of aluminium-based water treatment residual for potential phosphorus removal in engineered wetlands" Environmental Pollution. 157, 2830-2836.

Bai, Leilei., Wang, Changhui., He, Lainsheng., Pei Yuansheng. (2014). "Influence of the inherent properties of drinking water treatment residuals on their phosphorus adsorption capacities" Journal of Environmental Sciences 26, 2397-2405.

Bai, Leilei., Wang, Changhui., Huang, Caihong., He, Lainsheng., Pei Yuansheng. (2014). "Reuse of drinking water treatment residuals as a substrate in constructed wetlands for sewage tertiary treatment" Ecological Engineering 70, 295-303.

Bayley, R. M., Ippolito, J. A., Stromberger M. E., Barbarick, K.A., Paschke, M. W. (2008) "Water Treatment Residuals and Biosolids Coapplications Affect Semiarid Rangeland Phosphorus Cycling" Soil Science of America Journal 72, 711-719.

Carlson, W., Fitzpatrick, E., Flanagan, E., Kirschbaum, R., Williams, H., and Zickler, L. (2013). *Eastern Washington Low Impact Development Guidance Manual*. Washington State Department of Ecology.

Castaldi, Paola., Mele, Elena., Sivetti, Margherita., Garau, Giovanni., Deiana, Salvatore. (2013). "Water treatment residues as accumulators of oxoanions in soil. Sorption of arsenate and phosphate anions from an aqueous solution" Journal of Hazardous Materials 264, 144-152.

City of Fort Collins. (2011). *Bioretention Sand Media Specification*. Fort Collins, Colorado.

City of Portland. (2006). *Green Street Policy - Exhibit A*. Portland, Oregon.

Colorado Department of Public Health and Environment. (2012). *Regulation 85 - Nutrient Management Control Regulation*.

Colorado Department of Public Health and Environment. (2016). “CDPS General Permit COR090000 - Stormwater Discharges Associated with Municipal Separate Storm Sewer Systems (MS4s).”

Council of the City of Fort Collins. (2012). *Amending Chapter 26 of the Code of the City of Fort Collins and the Fort Collins Stormwater Criteria Manual to Incorporate Provisions Implementing Low Impact Development Principles*.

Dunets, C. S., Zheng, Y., and Dixon, M. (2015). “Use of phosphorus-sorbing materials to remove phosphate from greenhouse wastewater.” Environmental Technology, 36(14), 1759–1770.

Goh, H. W., Lau, T. L., Foo, K. Y., Chang, C. K., and Zakaria, N. A. (2015). “Influence of Hydraulic Conductivity and Organic Matter Content in Different Bioretention Media on Nutrient Removal.” *Applied Mechanics and Materials*, Trans Tech Publications, 802, 448–453.

Grebel, Janel E., Mohanty, Sanjay K, Torkelson, Andrew A., Boehm, Alexandria B., Higgins, Christopher P., Maxwell, Reed M., Nelson, Kara L., Sedlak, David L. (2013) “Engineered Infiltration Systems for Urban Stormwater Reclamation” Environmental Engineering Science, 30(8), 437-454.

Habibiandehkordi, Reza., Quinton John., Surridge Ben. (2014) “Effect of equilibration time on estimates of the maximum phosphorus sorption capacity of industrial by-products using the Langmuir model” Journal of Soil Sediments 14, 1818-1828.

Habibiandehkordi, Reza., Quinton John., Surridge Ben. (2015) “Can industrial by-products enhance phosphorus retention within vegetated buffer strips?” European Journal of Soil Science 66, 42-52.

Hsieh, C., and Davis, A. P. (2005). “Evaluation and Optimization of Bioretention Media for Treatment of Urban Storm Water Runoff.” *Journal of Environmental Engineering*, 131(11), 1521–1531.

Hunt, W. F., Jarrett, A. R., Smith, J. T., and Sharkey, L. J. (2006). “Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina.” *Journal of Irrigation and Drainage Engineering*, 132, 600–608.

Hunt, W., and Lord, W. (2006). “Bioretention Performance, Design, Construction, and Maintenance.” *North Carolina Cooperative Extension Service*.

Hurley, S., Shrestha, P., and Cording, A. (2017). “Nutrient Leaching from Compost: Implications for Bioretention and Other Green Stormwater Infrastructure.” *Journal of Sustainable Water in the Built Environment*, 3(3), 4017006.

Ippolito, J.A., Barbarick, K.A., Elliot H.A., (2011). “Drinking Water Treatment Residuals: A Review of Recent Uses” Journal of Environmental Quality, 40, 1-12.

Ippolito, J. A. (2015). “Aluminum-Based Water Treatment Residual Use in a Constructed Wetland for Capturing Urban Runoff Phosphorus: Column Study.” Water, Air, & Soil Pollution, Springer International Publishing, 226(10), 334.

Laird, D. A., Brown, R. C., Amonette, J. E., and Lehmann, J. (2009). "Review of the pyrolysis platform for coproducing bio-oil and biochar." *Biofuels, Bioproducts and Biorefining*, John Wiley & Sons, Ltd., 3(5), 547–562.

LeFevre, G. H., Paus, K. H., Natarajan, P., Gulliver, J. S., Novak, P. J., and Hozalski, R. M. (2015). "Review of Dissolved Pollutants in Urban Storm Water and Their Removal and Fate in Bioretention Cells." *Journal of Environmental Engineering*, 141(1), 4014050.

Li, Jiake., Davis, Allen P. (2016) "A unified look at phosphorus treatment using bioretention" Water Research 90, 141-155.

Liu, J., and Davis, A. P. (2014). "Phosphorus Speciation and Treatment Using Enhanced Phosphorus Removal Bioretention." *Environmental Science & Technology*, American Chemical Society, 48(1), 607–614.

Lim, H. S., Lim, W., Hu, J. Y., Ziegler, A., and Ong, S. L. (2015). "Comparison of filter media materials for heavy metal removal from urban stormwater runoff using biofiltration systems." Journal of Environmental Management, 147, 24–33.

Liu, Ranbin., Zhao, Yaqian., Sibille, Caroline., Ren, Baiming. (2016) "Evaluation of natural organic matter release from alum sludge reuse in wastewater treatment and its role in P adsorption" Chemical Engineering Journal 302, 120-127.

Logsdon, S. D., and Sauer, P. A. (2016). "Nutrient Leaching When Compost Is Part of Plant Growth Media." *Compost Science & Utilization*, Taylor & Francis, 24(4), 238–245.

Minnesota Pollution Control Agency. (2017). "Design criteria for bioretention." *Minnesota Stormwater Manual*, <https://stormwater.pca.state.mn.us/index.php/Design_criteria_for_bioretention> (Jun. 24, 2017).

Mortula, M. M., Gagnon, G. A. (2007) "Alum residuals as a low technology for phosphorus removal from aquaculture processing water" Aquacultural Engineering 36, 233-238.

Mullane, J. M., Flury, M., Iqbal, H., Freeze, P. M., Hinman, C., Cogger, C. G., and Shi, Z. (2015). "Intermittent rainstorms cause pulses of nitrogen, phosphorus, and copper in leachate from compost in bioretention systems." *Science of The Total Environment*, 537, 294–303.

Oladeji, Olawale O., O'Connor, George A., Saetain, Jerry B., Nair Vimala D. (2007) "Controlled Application Rate of Water Treatment Residual for Agronomic and Environmental Benefits" Journal of Environmental Quality, 36, 1715-1724.

Oladeji, Olawale O., O'Connor, George A., Brinton, Scott R. (2008) "Surface applied water treatment residuals affect bioavailable phosphorus losses in Florida sands" Journal of Environmental Management. 88, 1593-1600.

Paus, K. H., Morgan, J., Gulliver, J. S., and Hozalski, R. M. (2014). "Effects of Bioretention Media Compost Volume Fraction on Toxic Metals Removal, Hydraulic Conductivity, and Phosphorous Release." *Journal of Environmental Engineering*, 140(10), 4014033.

Philadelphia Water Department. (2017). "Green City, Clean Waters."

<http://phillywatersheds.org/what_were_doing/documents_and_data/cso_long_term_control_plan> (Jun. 22, 2017).

Reddy, Krishna, R., Xie, Tao. Dastgheibi, Sara. (2104) “Evaluation of Biochar as a Potential Filter Media for the Removal of Mixed Contaminants from Urban Storm Water Runoff” Journal of Environmental Engineering, 140(12), 1-10.

Rozari, P de., Greenway, M., Hanandeh, A. El., (2016) “Phosphorus removal from secondary sewage and septage using sand media amended with biochar in constructed wetland mesocosms” Science of the Total Environment, 569-570, 123-133.

Soleimanifar, H., Deng, Y., Wu, L., and Sarkar, D. (2016). “Water treatment residual (WTR)-coated wood mulch for alleviation of toxic metals and phosphorus from polluted urban stormwater runoff.” Chemosphere, 154, 289–292.

Stoner, Dustin., Penn, Chad., McGrath, Joshua., Warren, Jason. (2012) “Phosphorus Removal with By-Products in a Flow-Through Setting” Journal of Environmental Quality 41, 654-663.

Ulrich, B. A., Loehnert, M., and Higgins, C. P. (2017). “Improved contaminant removal in vegetated stormwater biofilters amended with biochar.” *Environ. Sci.: Water Res. Technol.*, Royal Society of Chemistry.

Urban Drainage and Flood Control District (UDFCD). (2011). *Urban storm drainage criteria manual*. *Vol. 3*, Denver, CO.

Vohla, Christina., Kõiv, Margit., Bavor, John H., Chazarenc, Florent., Mander, Ülo. (2011) “Filter materials for phosphorus removal from wastewater in treatment wetlands—A review” Ecological Engineering 37, 70-89.

Zhao, Y. Q., Babatunde, A. O., Razali M., Harty, F. (2008) “Use of dewatered alum sludge as a substrate in reed bed treatment systems for wastewater treatment” Journal of Environmental Science and Health Part A 43, 105-110.

Zhao, Y. Q., Babatunde, A. O., Hu, Y. S., Kumar J. L. G., Zhao, X. H. (2010) “A Two-Prong Approach of Beneficial Reuse of Alum Sludge in Engineered Wetland: First Experience from Ireland” Waste Biomass Valor 1 227-234.