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PERFORMANCE OF BIOCHAR IN BIORETENTION SYSTEM FOR REMOVAL OF MIXED CONTAMINANT: A REVIEW

SONG E.X.[1], ANURITA S.[2*], AAN M.N.A.[2],
TEO F.Y.[2], WONG C.F.[3] KOPPULA P.[4]

[1] Department of Chemical and Environmental Engineering, Faculty of Science and Engineering, University of Nottingham Malaysia, Jalan Broga, Semenyih, 43500 Selangor, Malaysia
[2] Department of Civil Engineering, Faculty of Science and Engineering, University of Nottingham Malaysia, Jalan Broga, Semenyih, 43500 Selangor, Malaysia
[3] Lee Kong Chien Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, (UTAR), 43000, Cheras, Kajang, Selangor, Malaysia
[4] Department of Botany, University College of Science, Osmania University, Hyderabad, Telangana, 500007, India

(*) anurita.selvarajoo@nottingham.edu.my

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ABSTRACT

Improper runoff management not only endangers human health but also threatens the ecosystem. Runoff often contains large amounts of organic and inorganic contaminants that create adverse impacts on the environment and cause a significant impediment to urban stormwater reuse. A bioretention system is a modern device that has been widely used; it is engineered to eliminate suspended solids and some other water-bound contaminants. Biochar, a carbon-rich byproduct produced from biomass pyrolysis, has proven to be effective in removing certain pollutants. This paper reviews the relevant applications of biochar filter media in bioretention systems and examines biochar's ability to remove E. coli, heavy metals, and nutrients. It also compares the performance of biochar produced under different operating conditions and provides further refinement of bioretention design parameters. Remarkably, biochar was reported as a promising adsorbent that is suitable to be amended to the bioretention system. Its high specific surface area, microporous carbonaceous structure, and negatively charged oxygen functional groups on the surface have created a strong affinity for mixed contaminant removal. More studies need to be conducted to encourage continuous quality improvement of the bioretention system.

Keywords: Biochar, Bioretention system, Filter media, Contaminant removal, Runoff treatment

INTRODUCTION

The area of impervious urban land has grown in response to rapid urbanization. With the city's unrestricted growth, impervious areas supersede the original landscape and hinder groundwater infiltration (Mohanty et al., 2014), necessitating the need to control runoff volumes and compromised water quality provoked by these areas (Li and Davis, 2016). This situation has resulted in more serious livestock and stormwater runoff, both of which have negative environmental and ecological effects (e.g., eutrophication and harmful algae blooms), as well as contaminating surface and groundwater (Ergas et al., 2021; Trowsdale and Simcock, 2011). Apart from that, the increasing surface runoff volume can degrade water quality by direct activation of corresponding pollutants (Mai and Huang, 2021). Urban stormwater runoff contains various amounts of heavy metals (Ma et al., 2016), excess organics and nutrients (i.e., nitrogenous and phosphorus matter) (Alam and Anwar, 2020), and bacteria (Lau et al., 2017). These pollutants can be hazardous to human health. Improper water runoff management may endanger receiving water environments, posing a significant obstacle to urban stormwater reuse (Ma et al., 2016).

To mitigate the detrimental effects of stormwater runoff, bioretention systems have been widely used as the best management practices (BMPs) (Davis et al., 2009) to resolve the hydrology, quality, and ecology of water bodies in urban as well as suburban areas (Hunt et al., 2012; LeFevre et al., 2015). It also acts as a common key component of the low impact development (LID) stormwater management philosophy, which is important in restoring predevelopment hydrology, reducing the rainfall runoff volume and controlling urban runoff pollution (Davis et al., 2009; Mai and Huang, 2021; Rahman et al., 2020). Bioretention systems are used to remove contaminants from polluted stormwater by filtering it through biologically active plants and soils (Trowsdale and Simcock, 2011), with people generally implementing them as a bioretention swale or bioretention basin. A retention system is frequently used for flood control, releasing it at a rate that prevents flooding or erosion while also settling suspended sediments and other solids. In contrast with the retention system, the bioretention system is made up of a soil bed planted with noninvasive (ideally native) vegetation that is located on top of a drain buried below the sand layer (Blick et al., 2004). Figure 1 shows the schematic diagram of a bioretention system (Davis et al., 2009). It may be under drained conditions, or runoff may seep into the subsoil. With bioretention, surface runoff is treated through sedimentation, adsorption, and filtration by vegetation, as well as infiltration within the soil bed. The system is composed of several layers of filter media (sand/soil/organic mixture), different types of vegetation, a storage pool with a depth of 15 to 30 cm, an overflow weir, and an optional underdrain (Jia Liu et al., 2014). Bioretention cells are generally small and treat catchment areas of less than 2 hectares (Hunt et al., 2008), with the system simulating the natural hydrologic cycle that retains runoff to reduce flow rates and volumes (Dietz, 2007). Figure 2 illustrates the laboratory bioretention columns (Subramaniam et al., 2014).

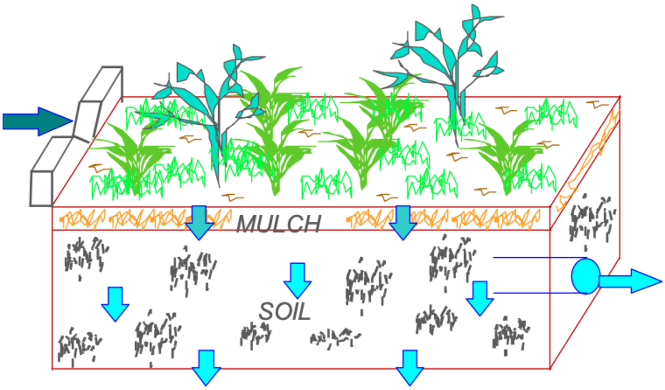

Figure 1: Schematic diagram of the bioretention system (Davis et al., 2009)

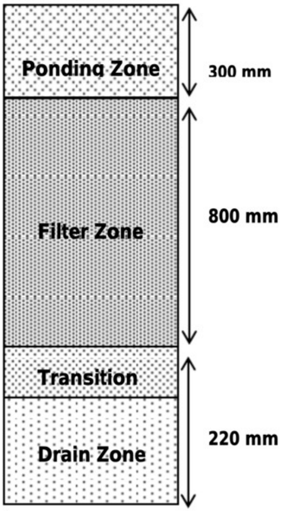

Figure 2: Schematic diagram of bioretention columns (Subramaniam et al., 2014)

However, despite its high pollutants (heavy metal, suspended solids, etc.) removal (S. Wang et al., 2017), the performance of bioretention systems in organic and nutrient removal is undesirable and highly variable (H. Li and Davis, 2009; Tian et al., 2019; H. Wang et al., 2021; Xiong et al., 2019; Zhong et al., 2019). The use of modified media as a critical factor in bioretention design can effectively improve runoff reduction, contaminant removal performance, and nutrient purification efficiency (Jia Liu et al., 2014; H. Wang et al., 2021). Biochar has recently gained popularity as a cost-effective and environmentally friendly filter medium for the treatment of numerous contaminants (Meng et al., 2021; Tian et al., 2019; Zhong et al., 2019). Biochar is a carbon-rich byproduct of the thermochemical decomposition of biomass (pyrolysis), which occurs when plant-based biomass is heated in a closed container with limited oxygen (Reddy et al., 2014). It has a wide range of applications, including soil amendment (Ding et al., 2016), nutrient and contaminant adsorption (Ahmad et al., 2014), greenhouse gas reduction, and energy generation (Cha et al., 2016). The negatively charged oxygen functional groups on the surface of biochar contribute to its high cation exchange capacity (Liang et al., 2006). Meanwhile, the porous carbonaceous structure and array of functional groups produced by the pyrolysis process also create an affinity for heavy metal removal (Ahmad et al., 2014; Akhil et al., 2021; Lehmann and Joseph, 2009). A noncarbonized fraction of biochar may interact with soil contaminants (Ahmad et al., 2014). The amount of O-containing carboxyl, hydroxyl, and phenolic surface functional groups in biochar, in particular, could efficiently bind with soil contaminants (Uchimiya et al., 2011). The multifunctional properties of biochar indicate that it has the potential to be a highly effective environmental sorbent for air, soil and water contaminants (Ahmad et al., 2014; Cha et al., 2016; Zhong et al., 2019). The detailed biochar qualities are highly influenced by pyrolysis temperature, residence time, structure and feedstock type. All of these factors have a significant impact on pollutant sorption effectiveness (Ahmad et al., 2014; Gray et al., 2014; Iqbal et al., 2015).

This paper seeks to review the current state of knowledge regarding biochar-amended bioretention systems and to incentivize broder use of this technology in enhancing runoff issues. We also compare the operating conditions and contaminant removal capacities of various biochar amendments, providing insights into biochar amendments in bioretention systems as well as further refinement of bioretention design parameters.

BIOCHAR-AMENDED BIORETENTION SYSTEM PERFORMANCE

Escherichia coli removal

Bacterial contamination of water is indeed one of the primary reasons why surface waters in the United States are impaired (Meals and Braun, 2006). Although many bacteria exist naturally, are widely distributed in the environment, and even play an important role in a variety of fundamental ecological processes, some of them might cause disease. Escherichia coli (also referred to as E. coli) is a type of bacteria found in intestines and feces. When there is a sufficient amount of E. coli present, pathogens are more likely to be present as well (Wolfson and Harrigan, 2010). Since runoff may wash over the feces of people and animals, it may contain a variety of pathogenic bacteria in varying concentrations, posing potential threats to public health and human health (Dorevitch et al., 2012). Concerning this issue, an analysis of the International Stormwater BMP database revealed that bioretention and sand filtration systems are the most viable BMPs for removing fecal indicator bacteria (FIB) from stormwater (Clary et al., 2014).

Nevertheless, broad variability in FIB removal has been reported and continues to be inadequate. Because the effect of conventional biofiltration media on the performance of FIB removal has been shown to be limited, bioretention systems (or biofilters) may be augmented with alternative engineered geomedia to improve the removal of microbial contamination (Kranner et al., 2019; Pitt and Clark, 2010). To date, many studies have presented the pros and cons of integrating biochar with bioretention systems for the removal of E. coli. Studies of E. coli removal by various biochars are summarized in Table 1.

General applications of biochar used in E. coli removal

Liu et al. (2020) proposed that the filter's specific surface area and porosity are perhaps the most significant factors influencing the removal effect. With its high specific surface area and microporous structure, biochar is expected to have excellent potential as an adsorbent or filter (Reddy et al., 2014). Bioretention systems amended with certain biochars have demonstrated improved microorganism removal from stormwater. A study that amended sand with 5 wt% biochar found that it retained up to 3 orders of magnitude more E. coli and minimized the mobilization of sequestered bacteria from a biofilter, thereby optimizing its overall removal rate (Mohanty et al., 2014). Similar findings were obtained in a recent study, where biochar-amended columns again proved to give better treatment performance in E. coli removal (Rahman et al., 2020). Moreover, in a 5-month laboratory study, Afrooz and Boehm (2017) discovered that biochar improved the removal of E. coli and enterococci in biofilters from natural stormwater. Additionally, as described by Kranner *et al.* (2019), biochar-amended sand biofilters remain desirable in simulated field settings after the 61-week conditioning phase. Biochar-amended sand filters outperformed sand biofilters in terms of E. coli removal. The result was particularly noticeable during the first 31 weeks of the conditioning phase and during the final challenge test (Kranner et al., 2019).

Effect of biochar modification

In addition, Lau et al. (2017) demonstrated how chemically modified biochar may promote the removal of bacteria in stormwater. Wood biochar is used and is then H_2SO_4-, H_3PO_4-, KOH-, and amino-modified. All biochars performed as promising filter media in the bioretention system, achieving excellent bacterial removal capacity and reducing the extent of remobilization under intermittent flow. H_3PO_4- and H_2SO_4-modified biochar showed an increased specific surface area and total pore volume compared to the original biochar, hence favoring E. coli adsorption. Generally, H_2SO_4 modification increased E. coli retention and significantly reduced subsequent remobilization, while other H_3PO_4 and KOH modifications had minimal influence. Meanwhile, the physicochemical properties of amino-modified biochar have changed significantly, resulting in a lower removal efficiency than that of the original biochar (Lau et al., 2017).

Effect of biochar feedstock and process production temperature

It is important to note that the efficacy will vary depending on the biochar feedstock and pyrolysis temperature. According to Sasidharan et al. (2016), biochar made from feedstocks such as macadamia shells, rice husks, wheat chaff, phragmites reeds, and oil mallee is not effective in E. coli and bacteriophage removal. Through a series of column experiments, Reddy, Xie and Dastgheibi (2014) investigated the ability of biochar as a filter media in removing mixed contaminants, including E. coli. The biochar selected was produced by waste wood pellets in a 520°C gasification process. In their study, biochar was not efficient in removing E. coli from stormwater since a low removal rate of 27% on average was observed. With respect to this issue, Lu and Chen (2018) demonstrated that wood dust-derived biochars pyrolyzed at different temperatures have distinctive efficiencies. In their findings, biochar pyrolyzed at the highest temperature (700°C) has been reported to provide greater E. coli removal efficiency due to its high specific surface area and pore volume (L. Lu and Chen, 2018). Abit et al. (2012) discovered similar results in regard to the effects of biochar pyrolysis temperature. Poultry litter and pine chip feedstocks were pyrolyzed at two temperatures (350 and 700°C). E. coli transport was significantly reduced in both biochars that were pyrolyzed at higher temperatures, with the pine chip biochars showing the maximum reductions. Low-temperature poultry litter biochar, on the other hand, increases transport, while low-temperature pine chip biochar decreases transport (Abit et al., 2012). When compared to other nonbiochar composite filters, the biochar-amended column (75% sand, 20% biochar, and 5% wood chips) demonstrated the best E. coli removal effect in bioretention systems (Jianwei Liu et al., 2020). The findings show that increasing the depth of the filter can improve the efficiency of E. coli removal. However, excessive depth of the submerged zone results in lower removal efficiency. Liu et al. (2020) concluded that drying reduced the effect on E. coli removal, but it could be restored by the rewetting process.

Table 1: Summary of biochar application studies collected for E. coli removal

Bioretention modification	Biochar type	Effectiveness	Reference
Biochar amendment in glass chromatography columns	Commercial biochar (Sonoma Compost Company, CA), two steam-activated biochars produced in laboratory via pyrolysis of wood chips at 350°C and 700°C	Effectively removed E. coli from an infiltrating solution in column experiments	Mohanty et al. (2014)
Biochar-amended filter media	Wood biochar (original, H_2SO_4-, H_3PO_4-, KOH-, and amino-modified)	Original biochar: 96.6% E. coli removal H2SO4-modified biochar: 98.7% E. coli removal H3PO4-modified biochar: 96.0% E. coli removal KOH-modified biochar: 96.4% E. coli	Lau et al. (2017)

		removal Amino-modified biochar: 92.1% E. coli removal	
Biochar-amended sand media	Biochar Supreme (pyrolyzed at 900-1000°C) and Biochar Now (pyrolyzed at 550°C)	Higher surface area of Biochar Supreme shows better E. coli removal than Biochar Now	Rahman, Nachabe and Ergas (2020)
Biochar-amended filter media	Waste wood pellets (gasification process at 520°C)	Biochar-augmented media was not efficient in removing E. coli from stormwater (27% mean removal efficiency)	Reddy, Xie and Dastgheibi (2014)
Biochar-amended biofilters	Commercial biochar (Sonoma Ecology Center, Eldridge, CA). Biochar feedstock consisted of 60% Monterey Pine, 20% Eucalyptus, 10% Bay Laurel, and 10% mixed hardwood and softwood	Saturated biochar: 0.78 ± 0.17 $\log_{10}$ removal values Unsaturated biochar: 0.45 ± 0.14 $\log_{10}$ removal values diminished over the conditioning phase	Kranner et al. (2019)
Biochar-amended column (75% sand, 20% biochar, and 5% wood chips)	-	Biochar-amended column had the best E. coli removal effect	Liu et al. (2020)
Biochar-augmented stormwater biofilters	60% Monterey Pine, 20% Eucalyptus, 10% Bay Laurel,10% mixed hardwood and softwood	Biochar-augmented biofilters effectively remove E. coli and enterococci from natural stormwater over nearly 5 months	Afrooz and Boehm (2017)
Biochar-amended sand columns in column experiment	Feedstocks of Macadamia Shell (MS), Oil Mallee (OM), Phragmites Reed (PR), Rice Husk (RH) and Wheat Chaff (WC).	Had no major effect on the removal of E. coli	Sasidharan et al. (2016)
Biochar-amended biofilters	Wood dust (pyrolyzed at 300, 500, and 700°C)	Biochar pyrolyzed at 700°C showed best E. coli removal efficiency (87.1%) compared to other biochars	Lu and Chen (2018)
Application of biochar in batch sorption	Poultry litter and pine chips	Effectively removed E. coli from an infiltrating solution in column experiments	Abit et al. (2012)
Biochar- and fungi amended sand columns in column experiment	-	Improved removal of E.coli, fecal coliform, total suspended solids and dissolved organic carbon	(Mitchell et al. 2023)

Heavy metal removal

Urban runoff is heavily polluted with toxic chemical pollutants such as heavy metals. These contaminants can pose a serious threat to human health, making them an impediment to the reuse of urban stormwater due to their toxicity levels (Ma et al., 2016; Wong et al., 2007), with zinc as the major concern, as it was found in extremely high concentrations. The Paul Matthews bioretention system that was installed in a field setting was assessed, and heavy metal capture, especially zinc, was not efficient since the dissolved Zn exiting the system still surpassed ecosystem health guidelines (Trowsdale and Simcock, 2011). The application of biochars in conjunction with advanced spectroscopic techniques has garnered tremendous attention in recent years given their huge potential in heavy metal removal and for elucidating the adsorption ability and binding mechanisms in aqueous solutions (Ippolito et al., 2012).

Biochar was shown to improve water retention, specific surface area, and cation exchange capacity. Its unique surface chemistry properties include enriched oxygen-containing groups and highly polarized graphitized carbon surfaces, all of which aid in the adsorption of persistent pollutants and the immobilization of toxic heavy metal ions (Cao et al., 2009; Z. Chen et al., 2015; L. Lu and Chen, 2018; Park et al., 2011; Thies and Rillig, 2009). Table 2 summarizes the biochar application studies collected for metal-contaminated water in the bioretention system.

Table 2: Summary of biochar application studies collected for metal-contaminated water in the bioretention system

Heavy metal contaminant	Biochar feedstock	Production temperature	Reference
Cd, Cu, Ni, Pb, Zn, Cr	Waste wood pellets (gasification process)	520°C	(Reddy et al., 2014)
Pb	Dairy manure (pyrolysis process)	200 and 350°C	(Cao et al., 2009)
Pb	Sludge (pyrolysis process)	550°C	(H. Lu et al., 2012)
Cu	Straw of peanut, soybean, and canola (pyrolysis process)	400°C	(Tong et al., 2011)
Cd, Cu, Ni, Zn	Broiler litter, alfalfa stems, switchgrass, corn cobs, corn stover, guayule bagasse, guayule shrubs, and soybean straw (pyrolysis process)	500°C	(Lima et al., 2010)
Cd, Cu, Zn	Dairy manure (pyrolysis process)	200 and 350°C	(Xu et al., 2012)
Cd, Cu, Pb	Peat moss (pyrolysis process)	400, 600, 800, and 1000°C (heating time 30, 60, and 90 min time)	(Lee et al., 2015)

Cd, Cu, Ni, Pb, Zn, As, Cr	Pine wood (pyrolysis process) Pine wood (gasification process) Pine wood (gasification process) Wood dust (pyrolysis process)	600°C >1100°C >1000°C 700°C	(Boehm et al., 2020)
Cd, Cu, Zn	Pine wood (pyrolysis process)	600°C	(Hasan et al., 2020)
Cu, Pb, Zn, As(V), PO_3^4	Oak tree (pyrolysis process)	285°C	(Q. Liu et al., 2019)
Cd, Cu, Pb, Zn, As	Pine wood (pyrolysis process)	600°C	(Hasan et al., 2021)
Pb(II), As(V), Cr(VI)	Bamboo (pyrolysis process)	-	(Zhou et al., 2014)
Zn	Enteromorpha prolifera (pyrolysis process)	400°C	(Su et al., 2022)

General applications of biochar used in heavy metal adsorption

Biochar produced from waste wood pellets by a gasification process at 520°C was used as a filter media in a series of column experiments, and it was discovered that certain heavy metal concentrations, such as Cd, Cr, Cu, Pb, Ni, and Zn, from urban stormwater runoff were significantly lowered Reddy, Xie and Dastgheibi (2014). It is proposed that the chemical behavior of heavy metals and the role of organic matter in the filter can directly influence the behavior and removal efficiency (Walker and Hurl, 2002). Lu et al. (2012) applied sludge-derived biochar to a batch sorption experiment with acidic solution. The total amount of Pb^{2+} sorbed through surface complexation with free carboxyl groups developed with increasing pH, suggesting that sludge-derived biochar is favorable for Pb^{2+} removal from specific acidic solutions with capacities ranging from 16.1-30.8 mg g^{-1} (H. Lu et al., 2012). Tong et al. (2011) demonstrated Cu(II) adsorption by biochars through surface complex formation with –COOH and phenolic hydroxyl groups on the biochar surfaces. The findings showed that peanut straw char had the highest adsorption capacity for Cu(II) of all the biochars tested, followed by soybean and canola straw-derived biochars. In general, crop straw biochares have a relatively higher Cu(II) adsorption capacity and could be employed as an adsorbent for removing Cu(II) from wastewater (Tong et al., 2011). In addition, Lima, Boateng and Klasson (2010) compared eight different biochars that have undeveloped structures of fast-pyrolysis biochar, namely, feedstock of broiler litter, alfalfa stems, switchgrass, corn cobs, corn stover, guayule bagasse, guayule shrubs, and soybean straw. The metal ion adsorption capacity was found to be feedstock dependent and varied according to activation, as the process encouraged access to highly reactive adsorption sites related to the feedstock's inorganic material. Overall, broiler litter and alfalfa stem-derived biochars have been shown to provide better yield and metal ion adsorption (Lima et al., 2010).

Biochar derived from dairy manure waste

Dairy manure waste has been used as a feedstock for biochar for heavy metal removal because it is rich in C, PO_4^{3-}, and CO_3^{2-}, which can serve as additional sorption sites (Uchimiya et al., 2010; Xu et al., 2012). The dairy manure-derived biochar produced at 350°C was more successful at adsorbing Cu, Zn and Cd than the biochar manufactured at 200°C. This study suggests that precipitation of PO_4^{3-} and CO_3^{2-} has a significant impact on retention capacity (Xu et al., 2012). The results showed that the biochar produced at 350°C demonstrated maximum Cu, Zn, and Cd sorption capacities of 54.4, 32.8, and 51.4 mg g^{-1}, respectively (Xu et al., 2012). However, another study that used dairy manure-derived biochar produced at 200°C showed higher sorption than biochar produced at 350°C, and it was found to be 6 times more effective than commercial activated carbon as a Pb sorbent (Cao et al., 2009). In this case, higher Pb removal by the biochar could be based on the precipitation of Pb-phosphate, and despite having the highest P content, the biochar produced at higher temperature (350°C) had the lowest soluble P content (Cao et al., 2009). The elevated temperature association of stable P-Ca-Mg could be one reason for the low soluble P (Cao et al., 2009). On the whole, dairy manure-derived biochar can be used as an effective heavy metal sorbent (Cao et al., 2009; Xu et al., 2012).

Effect of biochar production temperature and pH of solution

The biochar sorption capacity for heavy metals will differ from its physicochemical properties (Lee et al., 2015; Tong et al., 2011). Boehm *et al.* (2020) demonstrated that the removal longevity for various heavy metals varies depending on the process and temperature at which the biochar is produced. Based on the findings, biochar generally improves abiotic removal mechanisms (e.g., complexation, cation exchange, electrostatic interactions, precipitation, and chemical reduction) for Cu, Ni, and Zn, but not for the other metals, when compared to controls (column experiments with no biochar) (Boehm et al., 2020). Peat moss has also been used for heavy metal removal. Previous research on the heavy metal sorption capacity of peat moss and peat moss-derived biochar revealed that biochar improved metal adsorption by evolving the porous structure and increasing the pH (Hasan et al., 2020). In fact, Hasan et al. (2020) proposed that the pH of the solution was changed due to the speciation of metal ions, which had an impact on the complexation behavior of metals with functional groups on the surface. Nevertheless, for the removal of Pb and Cu, the biochar created by pyrolysis of peat moss at 800°C for 90 minutes was the most effective, as it has well-developed porous structures (Lee et al., 2015). The authors (Lee et al., 2015) also highlighted that micropores in peat moss-derived biochar prepared at 1000°C were observable, yet the majority of pore structures were destroyed and contracted.

Effect of biochar modification

The impact of surface modification is assessed by impregnating $Al_2(SO_4)_3$ solution on oak tree-derived biochar to investigate arsenate adsorption (Liu et al., 2019). Alimpregnated biochar demonstrated improved As(V) removal over pristine biochar in consecutive adsorption cycles. Liu et al. (2019) revealed that Al impregnation encourages the binding activities of As(V) toward the adsorbent and that the As(V) adsorption capability highly relies on the amount of aluminum hydroxide on the biochar. In addition, aluminum-impregnated biochar has shown great promise in removing Pb, Zn, Cu, and PO_4^3 from polluted urban runoff (Liu et al., 2019). Additionally, other studies have provided insights into the advantages of nanoscale zerovalent iron (nZVI) modification of biochar (Hasan et al., 2020, 2021; Zhou et al., 2014). It was indicated that nZVI-modified biochar outperformed unmodified biochar in terms of metal removal performance (Hasan et al., 2020). The development of C=O or C=C on the synthesized nZVI-modified biochar indicated that the functional groups on the biochar (C-O and -COOH) transformed to C-O-Fe, resulting in metal ion adsorption sites via the reduction reaction. Simultaneously, since metals (Cu^{2+}, Cd^{2+}, and Zn^{2+}) have a higher standard reduction potential than iron, Fe^0 and nZVI-modified biochar formation improved metal reduction (Hasan et al., 2020). Furthermore, a recent study showed that nZVI-modified biochar layered in sand as a filter medium delivered excellent As removal (up to 99%), which was attributed to high attachment to nZVI via surface complexation (Hasan et al., 2021). Both biochar layered in sand and a mixture of sand and biochar columns indicated convincing Cd and Zn uptake capacity, confirming that the negatively charged oxygen functional groups on the surface of biochar have great cation exchange potentials, which causes an affinity for the removal of heavy metals (Hasan et al., 2020, 2021). In addition, zerovalent iron (ZVI)-modified biochar derived from bamboo has been reported to be useful in sorbing Pb(II), Cr(VI), and As(V) heavy metals from aqueous solutions (Zhou et al., 2014). The authors (Zhou et al., 2014) indicated that Pb and Cr uptake was strongly influenced by reduction and surface adsorption mechanisms, while As(V) removal was most likely restricted to electrostatic attraction with the iron particles on the zerovalent iron (ZVI)-modified biochar surfaces. In addition, Li et al. (2020) proposed the significance of magnetic biochar in removing Cd(II), Pb(II), Zn(II), and Cu(II), and it was found that adsorption by magnetic biochar is more effective than that by common biochar. Further research on different biochar modifications should be carried out to improve the adsorption and removal mechanisms in bioretention systems.

Nutrient removal

Excessive nutrient loading has become a major threat to aquatic ecosystems and stormwater reuse. Nutrient pollutant removal, including nitrogen (N) and phosphorus (P), in the bioretention system has been recorded; however, the results obtained vary widely (Davis et al., 2009; Hsieh et al., 2007; Lucas and Greenway, 2008). It has been reported that biochar may be a useful amendment to bioretention systems to remove nutrient contaminants (Afrooz and Boehm, 2017; Reddy et al., 2014; Xiong et al., 2019; Yao et al., 2011). Nutrient adsorptions on various biochars in the aqueous phase are shown in Table 3.

Removal of nitrogen, phosphate, and ammonium

The addition of river sediment-derived biochar to bioretention media can affect the nutrient control of the system (Sang et al., 2019). In a bioretention column experiment performed by Sang et al. (2019), the nutrient removal efficiencies of river sediment-derived biochar and activated carbon were compared, and the results indicated that total nitrogen (TN) removal increased when biochar was used as an additive; however, the average mass removal efficiency of total phosphorus (TP) was better when activated carbon was added (Sang et al., 2019). In addition to these findings, Fellet et al. (2011) found that as the biochar content in the substrates increased, so did the pH, nutrient retention in terms of cation exchange capacity, and water-holding capacity.

Other studies also demonstrated biochar as a promising filter medium that improves the nutrient removal capacity of bioretention (Afrooz and Boehm, 2017) and can efficiently reduce the concentrations of nitrate and phosphate (Reddy et al., 2014). A prior study by Yao et al. (2011) assessed the phosphate removal performance of both undigested and anaerobically digested sugar beet tailings slowly pyrolyzed at 600°C, and the digested sugar beet tailing biochar demonstrated the highest phosphate removal rate (approximately 73%) in a laboratory adsorption experiment. The biochar-amended bioretention indicated greater removal rates for phosphate, ammonia, and total suspended solids (TSS) when compared to activated carbon, and the research revealed that this is mostly subject to the larger pore sizes of the biochar material than the microporous granular activated carbon (Huggins et al., 2016). Additionally, a recent field-scale experimental study reported that biochar that was evenly mixed with lateritic red soils had the best runoff pollutant removal capacity, including chemical oxygen demand (COD), TN, TP, NO_3-N, and NH_3-N (Mai and Huang, 2021). However, these findings are in accordance with the study demonstrated by (Iqbal et al., 2015), in which biochar modifications did not substantially reduce dissolved organic carbon (DOC), nitrate, and phosphate leaching when compared to the treatment that involved compost only.

Some studies have suggested that the application of ZVI has been shown to improve nitrogen removal (Liu et al., 2018) and phosphate removal in stormwater (Lechner, 2016). When ZVI and biochar were amended into bioretention cells, nitrate removal was increased, and water retention was improved (Tian et al., 2019). Alam and Anwar (2020) tested the ability of Eucalyptus wandoo biochar and alum sludge and their mixture in batches to absorb some nutrients from synthetic stormwater. The authors found that biochar alone could remove 100% of NO_2-N and NH_3-N, while alum sludge, on the other hand, was particularly successful in removing PO_4-P (100%) (Alam and Anwar, 2020). On top of these findings, Alam and Anwar (2020) found the optimum ratio of a mix medium consisting of 8 g biochar and 2 g alum sludge that can effectively remove NH_3-N, NO_2-N and PO_4-P maximum up to 98.2%, 99.4% and 99.8%, respectively. Similarly, NH_4–N was sorbed by both unwashed cacao shell and corn cob biochars, but there was no sorption of PO_4–P to either washed or rinsed biochars. Furthermore, no considerable NO_3-N release or sorption from or to either of the biochars was observed (Hale et al., 2013).

Effect of biochar modification

The removal efficiency of phosphate by magnetic biochars was investigated, and magnetic orange peel-derived biochar pyrolyzed at 250°C was reported to have significantly greater adsorption performance than nonmagnetic biochars (Chen et al., 2011). Nonetheless, a study also shows that amending iron-coated biochar as media can remove 94.6% of COD, 98.3% of ammonia, and 93.7% of TP (Xiong et al., 2019). Another study reported by Zhong et al. (2019) contributes a clearer understanding of the mechanisms influencing the phosphate adsorption of biochar. According to the findings, the adsorption capacity of coconut shell-derived biochar is intimately associated with pH, humic acid, and temperature, whereas the adsorption efficiency of iron-modified biochar is mainly influenced by ligand exchange and surface complexation with hydroxyl groups, electrostatic attraction, chemical precipitation, and inner-sphere complexation (Zhong et al., 2019).

Table 3: Summary of biochar application studies collected for nutrient adsorption in the aqueous phase

Nutrient	Biochar feedstock	Production temperature	Reference
TN, TP, NO_3-N, NH_3-N	Waste wood (pyrolysis process)	950°C	Mai and Huang (2021)
NH_3-N, NO_3-N, NO_2-N, PO_4-P	Eucalyptus wandoo (pyrolysis process)	400°C	Alam and Anwar (2020)
TN, TP, NH_4^+-N	Rice husk (pyrolysis process)	500°C	Xiong et al. (2019)
NO_3^-	Southern yellow pine wood (pyrolysis process)	550°C	Tian et al. (2019)
PO_4^{3-}	Coconut shell	-	Zhong et al. (2019)
NO_3^- PO_4^{3-}	Waste wood pellets (gasification process)	520°C	Reddy, Xie and Dastgheibi (2014)
NO_3^- PO_4^{3-}	Forest slash, Douglas fir (gasification process)	650°C	Iqbal, Garcia-Perez and Flury (2015)
NO^--N, NH_4^+-N, P	60% of Monterey Pine, 20% of Eucalyptus, 10% of Bay Laurel, 10% of mixed hardwood and softwood (pyrolysis process)	180-395°C	Afrooz and Boehm (2017)
PO_4^{3-}	Raw sugar beet tailings and anaerobically digested sugar beet tailings (pyrolysis process)	600°C	Yao et al. (2011)
TN, TP	River sediment (pyrolysis process)	400°C	Sang et al. (2019)

PO_4, NH_4	Lodgepole pine wood (pyrolysis process)	1000°C	Huggins et al. (2016)
PO_4–P, NH_4–N, NO_3–N	Cacao shell (pyrolysis process) Corn cob (pyrolysis process)	350°C 400°C	Hale et al. (2013)
PO_4^{3-}	Orange peel (pyrolysis process)	250, 400, and 700°C	Chen, Chen and Lv (2011)

These findings provide more information on biochar as a low-cost, environmentally friendly material for bioretention systems. Meanwhile, more research should be conducted to assess the commercial viability and long-term stability of biochar as a sorbent.

CONCLUSION

Overall, biochar was reported as a promising adsorbent that is suitable for amendment in bioretention systems. Its high specific surface area, microporous carbonaceous structure, and negatively charged oxygen functional groups on the surface have created a strong affinity for mixed contaminant removal. However, one species of biochar may not be able to successfully remove all types of contaminants, with feedstock type, production temperature, and process parameters all having a significant impact on the physical and chemical properties of biochar. Therefore, more studies need to be conducted to encourage continuous quality improvement of the bioretention system.

Declaration of competing interest

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

REFERENCES

ABIT S.M., BOLSTER C.H., CAI P., WALKER S.L.. (2012). Influence of feedstock and pyrolysis temperature of biochar amendments on transport of Escherichia coli in saturated and unsaturated soil, Environmental Science and Technology, Vol. 46, Issue 15, pp. 8097-8105.

AFROOZ A.R.M.N., BOEHM A.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, Vol. 102, pp. 320-330.

AHMAD M., RAJAPAKSHA A.U., LIM J.E., ZHANG M., BOLAN N., MOHAN D., VITHANAGE M., LEE S.S., OK Y.S.. (2014). Biochar as a sorbent for contaminant management in soil and water: A review, Chemosphere, Vol. 99, pp. 19-33.

AKHIL D., LAKSHMI D., KARTIK A., VO D-V N., ARUN J., GOPINATH K.P.. (2021). Production, characterization, activation and environmental applications of engineered biochar: a review, Environmental Chemistry Letters, Vol. 19, pp. 2261-2297.

ALAM M.Z, ANWAR A.H.M.F.. (2020). Nutrients adsorption onto biochar and alum sludge for treating stormwater, Journal of Water and Environment Technology, Vol. 18, Issue 2, pp. 132-146.

BLICK S.A., KELLY F., SKUPIEN J.J.. (2004). Bioretention Systems, In New Jersey stormwater best management practices manual, pp. 173-182.

BOEHM A.B., BELL C.D., FITZGERALD N.J.M., GALLO E., HIGGINS C.P., HOGUE T.S., LUTHY R.G., PORTMANN A.C., ULRICH B.A., WOLFAND J. M.. (2020). Biochar-augmented biofilters to improve pollutant removal from stormwater-can they improve receiving water quality? Environmental Science: Water Research and Technology, Vol. 6, Issue 6, pp. 1520-1537.

CAO X., MA L., GAO B., HARRIS W.. (2009). Dairy-Manure Derived Biochar Effectively Sorbs Lead and Atrazine, Environmental Science and Technology, Vol. 43, Issue 9, pp. 3285-3291.

CHA J.S., PARK S.H., JUNG S.C., RYU C., JEON J.K, SHIN M.C, PARK Y.K.. (2016). Production and utilization of biochar: A review, Journal of Industrial and Engineering Chemistry, Vol. 40, pp. 1-15.

CHEN B., CHEN Z., LV S.. (2011). A novel magnetic biochar efficiently sorbs organic pollutants and phosphate, Bioresource Technology, Vol. 102, Issue 2, pp. 716-723.

CHEN Z., XIAO X., CHEN B., and ZHU L.. (2015). Quantification of Chemical States, Dissociation Constants and Contents of Oxygen-containing Groups on the Surface of Biochars Produced at Different Temperatures, Environmental Science and Technology, Vol. 49, Issue 1, pp. 309-317.

CLARY J., PITT R., STEETS B.. (2014). Pathogens in Urban Stormwater Systems, Urban Water Resources, Research Council, American Society of Civil Engineers, Reston, VA. Research Council, American Society of Civil Engineers, Reston, VA.

DAVIS A.P., HUNT W.F., TRAVER R.G., CLAR M.. (2009). Bioretention Technology: Overview of Current Practice and Future Needs, Journal of Environmental Engineering, Vol. 135, Issue 3, pp. 109-117.

DIETZ M.E.. (2007). Low impact development practices: A review of current research and recommendations for future directions, Water, Air, and Soil Pollution, Vol. 186, Issue 1-4, pp. 351-363.

DING Y., LIU Y., LIU S., LI Z., TAN X., HUANG X, ZENG G., ZHOU L., ZHENG B.. (2016). Biochar to improve soil fertility. A review, Agronomy for Sustainable Development, Vol. 36, Issue 2, pp. 1-18.

DOREVITCH S., PRATAP P., WROBLEWSKI M., HRYHORCZUK D.O., LI H., LIU L.C., SCHEFF P.A.. (2012). Health risks of limited-contact Water recreation. Environmental Health Perspectives, Vol. 120, Issue 2, pp. 192-197.

ERGAS S.J, NACHABE M., RAHMAN M.Y.A., COOPER R.. (2021). Engineered bioretention design for control of nutrients and pathogens from agricultural runoff, Florida Department of Agriculture and Consumer Services (FDACS) Office of Agricultural Water Policy (OAWP).

FELLET G., MARCHIOL L., VEDOVE G.D., PERESSOTTI A.. (2011). Application of biochar on mine tailings: Effects and perspectives for land reclamation, Chemosphere, Vol. 83, Issue 9, pp. 1262-1267.

GRAY M., JOHNSON M.G., DRAGILA M.I., KLEBER M.. (2014). Water uptake in biochars: The roles of porosity and hydrophobicity, Biomass and Bioenergy, Vol. 61, pp. 196-205.

HALE S.E., ALLING V., MARTINSEN V., MULDER J., BREEDVELD G.D., CORNELISSEN G.. (2013). The sorption and desorption of phosphate-P, ammonium-N and nitrate-N in cacao shell and corn cob biochars, Chemosphere, Vol. 91, Issue 11, pp. 1612-1619.

HASAN M.S., GEZA M., VASQUEZ R., CHILKOOR G., GADHAMSHETTY V.. (2020). Enhanced Heavy Metal Removal from Synthetic Stormwater Using Nanoscale Zerovalent Iron–Modified Biochar, Water, Air, and Soil Pollution, Vol. 231, Issue 220 (2020).

HASAN M.S, VASQUEZ R., GEZA M.. (2021). Application of Biochar in Stormwater Treatment: Experimental and Modeling Investigation, Processes, Vol. 9, Issue 5, pp. 860.

HSIEH C., DAVIS A.P., NEEDELMAN B.A.. (2007). Bioretention column studies of phosphorus removal from urban stormwater runoff, Water environment research : a research publication of the Water Environment Federation, Vol. 79, Issue 2, pp. 177-184.

HUGGINS T.M., HAEGER A., BIFFINGER J.C, REN Z.J.. (2016). Granular biochar compared with activated carbon for wastewater treatment and resource recovery, Water Research, Vol. 94, pp. 225-232.

HUNT W.F., SMITH J.T., JADLOCKI S.J., HATHAWAY J.M., EUBANKS P.R.. (2008). Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, N.C, Journal of Environmental Engineering, Vol. 134, Issue 5, pp. 403-408.

HUNT W.F., DAVIS A.P., TRAVER R.G.. (2012). Meeting Hydrologic and Water Quality Goals through Targeted Bioretention Design, Journal of Environmental Engineering, Vol. 138, Issue 6, pp. 698-707.

IPPOLITO J.A., STRAWN D.G., SCHECKEL K.G., NOVAK J.M., AHMEDNA M., NIANDOU M.A.S.. (2012). Macroscopic and molecular investigations of copper sorption by a steam-activated biochar, Journal of Environmental Quality, Vol. 41, Issue 4, pp. 1150-1156.

IQBAL H., GARCIA-PEREZ M., FLURY M.. (2015). Effect of biochar on leaching of organic carbon, nitrogen, and phosphorus from compost in bioretention systems, Science of the Total Environment, Vol. 521-522, pp. 37-45.

KRANNER B.P., NABIUL AFROOZ A.R.M., FITZGERALD N.J.M., BOEHM A.B.. (2019). Fecal indicator bacteria and virus removal in stormwater biofilters: Effects of biochar, media saturation, and field conditioning, PLoS ONE, Vol. 14, Issue 9, pp. 1-23.

LAU A.Y.T., TSANG D.C.W., GRAHAM N.J.D., OK Y.S., YANG X., LI X.D.. (2017). Surface-modified biochar in a bioretention system for Escherichia coli removal from stormwater, Chemosphere, Vol. 169, pp. 89-98.

LECHNER L.S.. (2016). Phosphorus removal from stormwater using zero-valent iron. *Master Theses*. University of Delaware.

LEE S-J., PARK J.H., AHN Y-T., CHUNG J.W.. (2015). Comparison of Heavy Metal Adsorption by Peat Moss and Peat Moss-Derived Biochar Produced Under Different Carbonization Conditions, Water, Air, and Soil Pollution, Vol. 226, No. Issue 9 (2015), pp. 1-11.

LEFEVRE G.H., PAUS K.H., NATARAJAN P., GULLIVER J.S., NOVAK P.J., HOZALSKI R.M.. (2015). Review of Dissolved Pollutants in Urban Storm Water and Their Removal and Fate in Bioretention Cells, Journal of Environmental Engineering, Vol. 141, Issue 1, 04014050.

LEHMANN J., JOSEPH S.. (2009). Biochar for environmental management science and technology, Earthscan, London, Earthscan in the UK and USA.

LI H., DAVIS A.P.. (2009). Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention, Journal of Environmental Engineering, Vol. 135, Issue 8, pp. 567-576.

LI J., DAVIS A.P.. (2016). A unified look at phosphorus treatment using bioretention, Water Research, Vol. 90, pp. 141-155.

LI X., WANG C., ZHANG J., LIU J., LIU B., CHEN G.. (2020). Preparation and application of magnetic biochar in water treatment: A critical review, Science of The Total Environment, Vol. 711, pp. 134847.

LIANG B., LEHMANN J., SOLOMON D., KINYANGI J., GROSSMAN J., O'NEILL B., SKJEMSTAD O., THIES J., LUIZAO F.J., PETERSEN J., NEVES E.G.. (2006). Black Carbon Increases Cation Exchange Capacity in Soils, Soil Science Society of America Journal, Vol. 70, Issue 5, pp. 1719-1730.

LIMA I.M., BOATENG A.A., KLASSON K.T.. (2010). Physicochemical and adsorptive properties of fast-pyrolysis biochars and their steam activated counterparts. Journal of Chemical Technology and Biotechnology, Vol. 85, Issue 11, pp. 1515-1521.

LIU H., CHEN Z., GUAN Y., XU S.. (2018). Role and application of iron in water treatment for nitrogen removal: A review, Chemosphere, Vol. 204, pp. 51-62.

LIU J., SAMPLE D.J., BELL C., GUAN Y.. (2014). Review and research needs of bioretention used for the treatment of urban stormwater, Water (Switzerland), Vol. 6, Issue 4, pp. 1069-1099.

LIU J., YUE P., HE Y., ZHAO M.. (2020). Removal of E. coli from stormwater by bioretention system: parameter optimization and mechanism, Water Science and Technology, Vol. 81, Issue 6, pp. 1170-1179.

LIU Q., WU L., GORRING M., DENG Y.. (2019). Aluminum-Impregnated Biochar for Adsorption of Arsenic(V) in Urban Stormwater Runoff, Journal of Environmental Engineering, Vol. 145, Issue 4, 04019008.

LU H., ZHANG W., YANG Y., HUANG X., WANG S., QIU R.. (2012). Relative distribution of Pb2+ sorption mechanisms by sludge-derived biochar, Water Research, Vol. 46, Issue 3, pp. 854-862.

LU L., CHEN B.. (2018). Enhanced bisphenol A removal from stormwater in biochar-amended biofilters: Combined with batch sorption and fixed-bed column studies, Environmental Pollution, Vol. 243, pp. 1539-1549.

LUCAS W.C., GREENWAY M., (2008). Nutrient retention in vegetated and nonvegetated bioretention mesocosms, Journal of Irrigation and Drainage Engineering, Vol. 134, Issue 5, pp. 613-623.

MA Y., EGODAWATTA P., MCGREE J., LIU A., GOONETILLEKE A.. (2016). Human health risk assessment of heavy metals in urban stormwater, Science of The Total Environment, Vol. 557-558, pp. 764-772.

MAI Y., HUANG G.. (2021). Hydrology and rainfall runoff pollutant removal performance of biochar-amended bioretention facilities based on field-scale experiments in lateritic red soil regions,. Science of the Total Environment, Vol. 761, pp. 143252.

MEALS D.W., BRAUN D.C.. (2006). Demonstration of methods to reduce E. coli runoff from dairy manure application sites, Journal of Environmental Quality, Vol. 35, Issue 4, pp. 1088-1100.

MENG Y., WANG Y., WANG C.. (2021). Phosphorus release and adsorption properties of polyurethane–biochar crosslinked material as a filter additive in bioretention systems, Polymers, Vol. 13, Issue 2, pp. 1-17.

MITCHELL C.J, JAYAKARAN A.D, MCINTYRE J.K.. (2023). Biochar and fungi as bioretention amendments for bacteria and PAH removal from stormwater, Journal of Environmental Management, Vol. 327, pp. 116915.

MOHANTY S.K., CANTRELL K.B., NELSON K.L., BOEHM A.B., (2014). Efficacy of biochar to remove Escherichia coli from stormwater under steady and intermittent flow, Water Research, Vol. 61, pp. 288-296.

PARK J.H., CHOPPALA G.K., BOLAN N.S., CHUNG J.W., CHUASAVATHI T.. (2011). Biochar reduces the bioavailability and phytotoxicity of heavy metals. Plant and Soil, Vol. 348, Issue 1, pp. 439-451.

PITT R., CLARK S., STEETS B.. (2010). Evaluation of the contaminant removal potential of biofiltration media, Low Impact Development 2010@ sRedefining Water in the City, ASCE, pp. 533-546.

RAHMAN M.Y.A., NACHABE M.H., ERGAS S.J.. (2020). Biochar amendment of stormwater bioretention systems for nitrogen and Escherichia coli removal: Effect of hydraulic loading rates and antecedent dry periods, Bioresource Technology, Vol. 310, Issue April, pp. 123428.

REDDY K.R, XIE T., DASTGHEIBI S.. (2014). Evaluation of Biochar as a Potential Filter Media for the Removal of Mixed Contaminants from Urban Storm Water Runoff, Journal of Environmental Engineering, Vol. 140, Issue 12, pp. 04014043.

SANG M., HUANG M., ZHANG W., CHE W., SUN H.. (2019). A pilot bioretention system with commercial activated carbon and river sediment-derived biochar for enhanced nutrient removal from stormwater, Water Science and Technology : A Journal of the International Association on Water Pollution Research, Vol. 80, Issue 4, pp. 707-716.

SASIDHARAN S., TORKZABAN S., BRADFORD S.A., KOOKANA R., PAGE D., COOK P.G.. (2016). Transport and retention of bacteria and viruses in biochar-amended sand, Science of The Total Environment, Vol. 548-549, pp. 100-109.

SU Z., SUN P., CHEN Y., LIU J., LI J., ZHENG T., YANG S.. (2022). The influence of alkali-modified biochar on the removal and release of Zn in bioretention systems: Adsorption and immobilization mechanism, Environmental Pollution, Vol. 310, pp. 119874.

SUBRAMANIAM D.N., EGODAWATTA P., MATHER P.B., RAJAPAKSE J.. (2014). Stabilization of experimental bioretention basins during intermittent wetting and drying, In Proc., Stormwater Queensland Conf.: Visions to Realities, Noosa Heads, Queensland, Australia.

THIES J.E., RILLIG M.C.. (2009). Characteristics of Biochar: Biological Properties, J. Lehmann and S. Joseph, Éd., Biochar for Environmental Management (1re éd.). Routledge.

TIAN J., JIN J., CHIU P.C., CHA D.K., GUO M., IMHOFF P.T. (2019). A pilot-scale, bilayer bioretention system with biochar and zero-valent iron for enhanced nitrate removal from stormwater, Water Research, Vol. 148, pp. 378-387.

TONG X.J, LI J.Y., YUAN J.H., XU R.K.. (2011). Adsorption of Cu(II) by biochars generated from three crop straws, Chemical Engineering Journal, Vol. 172, Issue 2, pp. 828-834.

TROWSDALE S.A., SIMCOCK R.. (2011). Urban stormwater treatment using bioretention, Journal of Hydrology, Vol. 397, Issue 3-4, pp. 167-174.

UCHIMIYA M., KLASSON K.T., WARTELLE L.H., LIMA I.M.. (2011). Influence of soil properties on heavy metal sequestration by biochar amendment: 1. Copper sorption isotherms and the release of cations, Chemosphere, Vol. 82, Issue 10, pp. 1431-1437.

UCHIMIYA M., LIMA I.M., KLASSON K.T., CHANG S., WARTELLE L.H., RODGERS J.E.. (2010). Immobilization of heavy metal ions (CuII, CdII, NiII, and PbII) by broiler litter-derived biochars in water and soil, Journal of Agricultural and Food Chemistry, Vol. 58, Issue 9, pp. 5538-5544.

WALKER D.J., HURL S.. (2002). The reduction of heavy metals in a stormwater wetland, Ecological Engineering, Vol. 18, Issue 4, pp. 407-414.

WANG H., GAN H., ZHANG Z., YU Z., ZHU D.Z.. (2021). Purification efficiency of bioretention with modified media under varied rain intensity and drying conditions, Journal of Environmental Engineering, Vol. 147, Issue 4.

WANG S., LIN X., YU H., WANG Z., XIA H., AN J., FAN G.. (2017). Nitrogen removal from urban stormwater runoff by stepped bioretention systems, Ecological Engineering, Vol. 106, pp. 340-348.

WOLFSON L.G., HARRIGAN T.. (2010). Cows, Streams, and E. Coli: What everyone needs to know, https://www.canr.msu.edu/uploads/resources/pdfs/cows,_streams,_and_e._coli_-_what_everyone_needs_to_know_(e3103).pdf

WONG M.H., WU S.C., DENG W.J., YU X.Z., LUO Q., LEUNG A.O.W., WONG C.S.C., LUKSEMBURG W.J., WONG A.S.. (2007). Export of toxic chemicals - A review of the case of uncontrolled electronic-waste recycling, Environmental Pollution, Vol. 149, Issue 2, pp. 131-140.

XIONG J., REN S., HE Y., WANG X.C., BAI X., WANG J., DZAKPASU M.. (2019). Bioretention cell incorporating Fe-biochar and saturated zones for enhanced stormwater runoff treatment, Chemosphere, Vol. 237. 124424.

XU X., CAO X., ZHAO L., WANG H., YU H., GAO B., (2012). Removal of Cu, Zn, and Cd from aqueous solutions by the dairy manure-derived biochar, Environmental Science and Pollution Research, Vol. 20, pp. 358-368.

YAO Y., GAO B., INYANG M., ZIMMERMAN A.R., CAO X., PULLAMMANAPPALLIL P., YANG L.. (2011). Removal of phosphate from aqueous solution by biochar derived from anaerobically digested sugar beet tailings, Journal of Hazardous Materials, Vol. 190, Issue 1-3, pp. 501-507.

ZHONG Z., YU G., MO W., ZHANG C., HUANG H., LI S., GAO M., LU X., ZHANG B., ZHU H., (2019). Enhanced phosphate sequestration by Fe(III) modified biochar derived from coconut shell, RSC Advances, Vol. 9, Issue 18, pp. 10425-10436.

ZHOU Y., GAO B., ZIMMERMAN A.R., CHEN H., ZHANG M., CAO X., (2014). Biochar-supported zerovalent iron for removal of various contaminants from aqueous solutions, Bioresource Technology, Vol. 152, pp. 538-542.