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Compaction conditions affect the capacity of biochar-amended sand filters to treat road runoff

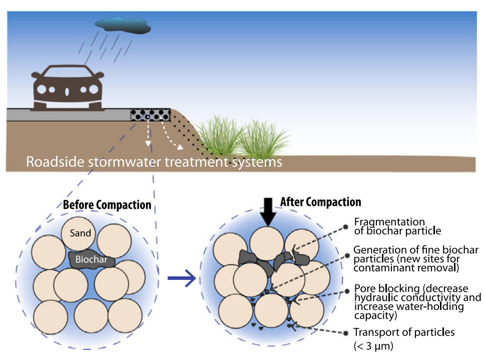
Maryam Ghavanloughajar [a], Renan Valenca [a], Huong Le [a], Merrick Rahman [a], Annesh Borthakur [a], Sujith Ravi [b], Michael K. Stenstrom [a], Sanjay K. Mohanty [a,*]

[a] Department of Civil and Environmental Engineering, University of California, Los Angeles, USA
[b] Department of Earth and Environmental Science, Temple University, Philadelphia, USA

HIGHLIGHTS

- Wet-compacted columns released more biochar particles than dry-compacted columns.
- Net initial loss of biochar particles due to compaction was insignificant.
- Compaction decreased hydraulic conductivity, but the presence of water reduced the impact.
- Compaction increased stormwater interaction with filter media.
- Wet-compacted columns removed more *E. coli* than dry-compacted columns.

GRAPHICAL ABSTRACT



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ABSTRACT

Amending roadside soil with adsorbents such as biochar can help remove pollutants from road runoff. To maintain soil stability, the roadside soil requires compaction. However, it is unknown how compaction conditions affect the capacity of biochar-augmented roadside biofilters to infiltrate stormwater and remove pollutants. This work examines the effect of compaction conditions on the release of biochar particles disintegrated during compaction, and the change in their capacity to infiltrate stormwater and remove *E. coli*. The net loss of biochar particles by mobilization with stormwater was insignificant compared to the biochar remained in the filters. The initial release of biochar particles in wet-compacted biochar columns was greater than that in dry-compacted biochar. The results revealed that compaction can affect the release of biochar particles in a series of three-step processes: generation of particles by disintegration of large biochar under compaction, diffusion of particles deposited near grain walls to bulk pore water, and transport and retention of particles in constricted pore paths based on pore water connectivity. Under similar conditions, compost columns released more particles than biochar columns, suggesting biochar is more stable than compost under compaction. *E. coli* removal in wet-compacted columns was greater than removal in dry-compacted columns, owing to greater pore path connectivity in wet-compacted columns. These results indicate that addition of moisture during compaction can increase contaminant removal, initial particle release, and infiltration capacity of biochar-augmented sand filters for road runoff treatment. The results would help develop design guidelines for roadside stormwater treatment systems that require compaction of filter media.

* Corresponding author.
E-mail address: mohanty@ucla.edu (S.K. Mohanty).

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1. Introduction

Road infrastructures help economic growth, but road runoff is also one of the major sources of pollutants. Stormwater runoff washes off pollutants deposited on impervious surfaces on and around the road during dry weather and conveys them to waterbodies (Cambi et al., 2015). To minimize pollution from road runoff, roadside green infrastructures can be implemented where pollutants can be removed from road runoff as it infiltrates through roadside soil mixed with amendments. These roadside green infrastructures could also provide additional benefits including groundwater recharge, carbon sequestration, and ecological habitat restoration (Wong et al., 2000). To prevent landslide and increase soil stability, the roadside soils, however, are compacted—a practice not recommended for infiltration-based green infrastructure in order to maintain its infiltration capacity. Thus, it is critical to examine whether or how compaction may affect the performance of infiltration-based green infrastructure, so that a design guideline for roadside green infrastructure with compaction can be developed (Pereira et al., 2017; Sax et al., 2017).

Only a couple of studies have examined the effect of compaction on the performance of stormwater treatment systems (Pitt et al., 2008; Mossadeghi-Bjorklund et al., 2016), and these studies showed that compaction can reduce hydraulic conductivity of soil and lower stormwater infiltration. Amendments such as compost and biochar have been used to improve the contaminant removal capacity of stormwater biofilters (Boehm et al., 2020; Sun et al., 2020). Biochar, a carbonaceous porous medium produced by pyrolysis of wood or biomass, has been shown to exhibit higher removal capacity than any other conventional biofilter media for a wide range of pollutants, including heavy metals, organic contaminants, nutrients, and pathogens (Lau et al., 2017; Mohanty et al., 2018). High capacity of biochar has been attributed to high carbon content, porous structure with high surface area, high cation exchange capacity, and redox-active surfaces to aid transformation of attached pollutants.

Treatment capacity of biochar-augmented biofilters subjected to compaction has not been evaluated, partly because compaction may not be recommended in most cases. In some cases, however, compaction of biochar-amended media may naturally occur or is required (e.g., road bank, permeable pavement, or land cover for landfills). The extent to which compaction may affect their physical integrity of biochar and their ability to treat stormwater is unknown (Mohanty et al., 2018). Many studies have examined the effect of biochar addition on hydraulic and mechanical properties of soil after compaction (Ahmed et al., 2017; Liu et al., 2017; Ahmed and Raghavan, 2018; Menon et al., 2018), but these studies rarely examined how compact would affect biochar properties (e.g., size). For example, biochar size could change under compaction due to fragmentation of biochar particles; similarly, biochar size and quantity can influence the dissipation of energy from compaction.

The long-term performance of biochar in biofilters depends on the physiochemical integrity of biochar, which can be changed by compaction. As biochar particles have lower load-bearing capacity than other media such as woodchips (Reza et al., 2012), compaction could break biochar grains, release small suspended particles, and increase the loss of these biochar particles by erosion during stormwater infiltration. On the other hand, compaction could also constrict the flow paths and minimize the mobility of biochar particles. Thus, the net leaching potential of biochar particles during compaction could depend on two competing factors: the quantity of biochar particles created during compaction (source-limited factor) and the fraction of the particle pool mobilized during the infiltration of stormwater (transport-limited factor). Initial moisture content affects the degree of compaction of soil (Henderson et al., 2005). Increases in moisture content until a critical moisture value initially help compacting the soil because water helps slide soil particles under compaction stress; increases in moisture content beyond the critical moisture value prevent soil particles to come closer under compaction because of the presence of the excess water, an incompressible fluid, between soil particles. Thus, the presence of moisture during compaction could be a critical factor in affecting the release of biochar particles after compaction. It is unclear how compaction affects the erosion potential of biochar and other types of particles such as compost in biofilters (Kumar et al., 2019). As biochar particles could contain a high concentration of adsorbed contaminants, the release of particles may lead to an increase or even exceedance of the concentration of contaminants in the effluent (Mohanty et al., 2013). Because compaction can reduce the net porosity of filter media, it may decrease the infiltration capacity of biofilters (Sileshi et al., 2016). As compaction can alter the way water moves through pore spaces, it could affect the removal of contaminants such as bacterial pathogens. To what extent compaction may affect infiltration and bacterial removal capacity of biochar-augmented biofilters is unknown.

This work aims to quantify the effect of compaction on the biofilter's performance, which includes changes in hydraulic conductivity, flowpath heterogeneity, leaching of biochar particles, and removal of pathogen-indicator bacteria. We used a reductionist approach using a sand filter augmented with biochar or compost to isolate specific processes and examine the impact of compaction on specific factors. We hypothesized that the effect of compaction on the net loss of biochar particles is dependent on media type and moisture content during compaction. Furthermore, we evaluated the utility of engineering controls such as compost and initial moisture content to test their role in minimizing the detrimental effect of compaction on biochar-augmented biofilter.

2. Materials and methods

2.1. Stormwater

To discern the effect of physical factors such as compaction on the release of biochar particles during infiltration events, the ionic strength and pH—the factors that affect particle release—were kept constant. Natural stormwater was collected twice a week in 20-L HDPE plastic carboys from Ballona Creek in Los Angeles, CA (34° 0′36" N, 118° 23′ 29" W), which receives dry-weather irrigation runoff from a 318 km^2 urban area with 82% developed and 61% impervious surface (Gold et al., 2015). Stormwater was characterized for pH (8.0 $\pm$ 0.5) and conductivity (900 $\pm$ 100 $\mu S\ cm^{-1}$) within 1 h of sample collection. Synthetic stormwater was prepared by adding 10 mM NaCl to DI water so that the electrical conductivity (900 $\pm$ 50 $\mu S\ cm^{-1}$), as an indicator of ionic strength or total dissolved solid, is similar to that of the natural stormwater from Los Angeles. pH was adjusted to 7.8 $\pm$ 0.2 by adding a small volume of concentrated HCl or NaOH. pH and electrical conductivity are key water quality parameters that could affect release of particles from filter media. Unlike synthetic stormwater, the natural stormwater may contain other pollutants and constituents (McPherson et al., 2002; Brown et al., 2013).

A kanamycin-resistant *Escherichia coli* strain (NCM 4236) was used to distinguish the applied *E. coli* from other *E. coli* strains present naturally in stormwater. *E. coli* were suspended in stormwater following a method outlined elsewhere (Mohanty et al., 2014). Briefly, *E. coli* were cultured to a stationary phase, centrifuged and washed with phosphate buffer solution to remove the growth medium, and suspended in the collected stormwater to achieve an initial concentration of nearly 10^5 colony forming units (CFU) mL^{-1}.

2.2. Biofilter media

Commercially available biochar (Black Owl Biochar™, Biochar Supreme, WA), sand (20–30 Ottawa Sand, Certified Material Testing Products, FL), and garden compost (Whitter Fertilizer, CA) were used in this study. The biochar, produced by gasification of a softwood at high temperature (900–1000 °C), exhibits high BET surface area (800 $m^2\ g^{-1}$)

and low ash content (5.8%) (Table S1). Typically pyrolysis of biomass can alter its physical properties and decreases its mechanical strength (Reza et al., 2012). Thus, it is expected biochar would be more susceptible to breakage under compaction than the feedstock used for the biochar production. Sand was used because it is commonly applied to increase stormwater infiltration, whereas compost was used to increase pollutant removal with added benefit of their ability to alleviate the effect of compaction (Sax et al., 2017). To remove silica colloids from sand, sand was washed in deionized (DI) water and dried in an oven. Biochar and compost were sieved to remove particles smaller than 833 μm—the mean size of sand particles— to ensure that any fine particles released in the effluent were generated during the packing of media under compaction in the columns. Particles larger than 2 mm were also removed to minimize preferential flow.

The typical biofilter media may contain 10–30% amendment to increase pollutant removal. We mixed sand (85% by volume) with biochar or compost (15% by volume) in a sterile 4-L bucket, to compare the effect of compaction on biochar and compost—the widely used soil amendment to alleviate compaction effect. The media was mixed manually for 5 min to ensure a uniform mixture. We mixed same volume of compost and biochar (15% of each) with sand (70% by volume) to examine whether addition of biochar would affect the treatment capacity of compost-biofilter after compaction. We compacted biochar-sand mixture without and with water (15% by weight) to examine how the presence of moisture during compaction affects the treatment capacity of compacted biochar. We chose 15% moisture content because it is the optimum moisture content for maximum dry density after compaction of poorly grade sand (Deb, K. 2010), although the critical moisture content for biochar-sand mixture could be different. The mixtures were immediately used to pack the columns after preparation. It should be noted that we did not include sand-only column because, unlike biochar or compost or soil, sand is not affected by compaction. Physical properties of compacted mixtures are described in Table 1. Additionally, the particle size distributions of the mixtures were determined using a laser diffraction particle size analyzer (model LS 13320, Beckman Coulter, CA).

2.3. Packing of filter media in columns

To design a laboratory column setup, a transparent PVC tube (5.1 cm ID and 61.0 cm length) was glued with PVC fittings and connected to a control valve to regulate the effluent flow. A total of 15 columns were packed with the following media mixture with sand under different compaction conditions: uncompacted biochar, compacted biochar under dry condition, compacted biochar under wet condition, compacted compost, compacted biochar and compost. Each mixture was packed in triplicate columns (Fig. S1).

Before packing the filter media in each column, a 6-cm drainage layer was created in the bottom of the column using nylon membranes (100 μm pores) and pea gravels. The media mixture was added incrementally and compacted to a height of a 3.8-cm layer using a standard Proctor hammer (2.5 kg). To ensure that comparable energy of a standard Proctor test was applied on the filter media, the hammer was dropped 7 times from 30.4 cm height per layer. The procedure was repeated for 8 layers so that the total height of the filter layer became 30.4 cm. The bulk density was estimated after compaction of each layer to ensure uniform distribution of filter media by depth (Fig. S2). A 2.5-cm layer of pea gravels was added on the top of filter media to prevent biochar or compost particles to float in the event of ponding. The total pore volume (PV) of the filter layer and the porosity of each column are summarized in Table 1. More information on packing methodology and determination of pore volume and porosity can be found in the Supplementary Material.

Experiments were conducted using the same columns in the following order to determine the effects of compaction on (1) initial release of particles, (2) hydraulic conductivity of packed media, (3) flow-path connectivity via tracer study, and (4) *E. coli* removal capacity of the columns. The particle release experiment was conducted at the beginning in order to examine the immediate effect of compaction on particle release. The next two experiments helped determine the change in hydraulic properties of filter media following compaction. The *E. coli* experiment was conducted at the end to correlate any change in removal capacity to changes in hydraulic properties of columns after compaction. Between each experiment, the columns were drained by gravity and kept it for 2–3 days.

2.4. Release of particles during the infiltration of stormwater

To examine the release of biochar particles during application of stormwater, synthetic stormwater (10 mM NaCl) was used so that the influent water would be particulate free. Synthetic stormwater (2 PV) was applied on the top of the filter media at a flow rate of 5 mL min^{-1} or flux of 14.8 cm h^{-1}, following which the filter media was drained by gravity. We expect that increases in flow rate can increase particle release (Shang et al., 2008) and decrease bacterial removal (Mohanty and Boehm, 2014b). We used a fixed velocity to rule out the effect of flow fluctuation on the results. Effluents were collected in 250 mL amber bottles at 0.5 PV fractions and analyzed for particle concentration and volume. The experiment was repeated for five consecutive days beyond which particle release did not change with successive infiltration events. Particle concentration in the effluent samples was estimated by measuring the absorbance at 890 nm—the wavelength used to determine turbidity—using a UV–Vis Spectrophotometer (Lambda 365, PerkinElmer) and correlating the absorbance with concentration using a calibration curve. The particle size distribution of the effluent was measured using a single-particle optical sensor instrument (AccuSizer 780, Entegris Company). More information on sample measurement can be found in Supplementary Material.

Table 1
Hydraulic characteristics and design parameters of laboratorial biofilters. Each biofilter type was constructed in triplicated ($n = 15$). Mean and standard deviation over mean for each parameter was estimated from measurements in triplicate columns.

Biofilter type	Sand (%)	Compost (%)	Biochar (%)	Moisture content (w/w) (%)	Compaction	Bulk density (g cm^{-3})	Pore volume of filter layer (mL)	Pore volume including drainage layer (mL)	Porosity (%)
Uncompacted biochar (dry)	85	0	15	0	No	1384.4 ± 39.8	205.23 ± 6.2	284.3 ± 1.5	33.2 ± 1.0
Compacted biochar (dry)	85	0	15	0	Yes	1579.2 ± 42.3	192.27 ± 2.2	253.5 ± 5.1	31.1 ± 0.4
Compacted biochar (wet)	85	0	15	15	Yes	1384.3 ± 72.5	232.07 ± 9.3	305.7 ± 10.9	37.6 ± 1.5
Compacted compost and biochar (dry)	70	15	15	0	Yes	1547.8 ± 79.9	187.70 ± 11.6	266.4 ± 5.0	30.4 ± 1.9
Compacted compost (dry)	85	15	0	0	Yes	1377.3 ± 50.1	204.75 ± 8.6	279.0 ± 9.3	33.2 ± 1.4

2.5. Measurement of hydraulic conductivity

Hydraulic conductivity (K) of each column was measured using a falling head method using the equation: $K = \frac{L}{t}\ \ln(\frac{h_0}{h_t})$, where L is the depth of filter media, t is the time to drain water from initial height h_0 to final height h_t after drainage of a specific volume of water. Briefly, 2 PV of synthetic stormwater (without particulates) was applied on the top of packed media to permit free drainage of stormwater at the bottom valve. The effective hydraulic conductivity of biofilters was estimated by recording the time required to drain a specific volume of stormwater. The procedure was repeated 6 times to estimate the average hydraulic conductivity of each column.

2.6. Measurement of effective pore volume and flow path heterogeneity

We measured effective pore volume, the fraction of total pore space filled with stormwater during an infiltration event, by estimating the volume of stormwater injected to achieve 50% of the concentration of bromide (a conservative tracer) in the feed solution (Ptak et al., 2004). Briefly, synthetic stormwater containing bromide (9 mM NaCl +1 mM KBr) was applied on the top of each column at 5 mL min^{-1} for 2 h before applying 10 mM NaCl for additional 2 h to flush bromide from pore water. The flow was interrupted for 12 h, followed by injection of 10 mM NaCl for additional 0.7 h to compare the extent of diffusion-limited regions in different media mixture (Brusseau et al., 1997). We used the ratio of bromide concentration before and after flow interruption as an indicator of the presence of diffusion-limited zones in the biochar-augmented sand filters, as compaction is expected to create low-permeable zones or flow-stagnant zones, where diffusion would be significant for the transport of solute in between rainfall events.

2.7. E. coli removal

Stormwater contains a wide range of pollutants. However, we chose *E. coli* to test removal of particulate pollutants as the removal process based on physical filtration is most likely to be affected by change in pore structure under compaction. Furthermore, presence of pathogen or indicator bacteria is the lead cause of water quality violation in Los Angeles area. Pathogens can be removed in biofilters by a combination of processes including physico-chemical filtration, inactivation, gazing, and natural die-off via starvation or drying (Rippy, 2015). We hypothesize that compaction could increase bacterial removal via physico-chemical filtration by decreasing pore size. To investigate the effect of compaction on removal of *E. coli*, 5 PV of natural stormwater spiked with *E. coli* (concentration ~ 10^5 CFU mL^{-1}) was applied at 5 mL min^{-1} on the top of each column, and effluent samples were collected at the bottom. The concentration of *E. coli* was measured in the last 0.5 PV fraction of the samples, which serves as an indicator for the steady-state removal capacity of the filter. We did not measure *E. coli* concentration during first-flush because the previous study with biochar (Mohanty et al., 2014) showed that the concentration of *E. coli* in the first flush (old water in the column) were lower than that of pore water collected in the last part of infiltration events, due to inactivation or increased adsorption of *E. coli* trapped in pore water during period between rainfall events. *E. coli* concentration in stormwater was quantified by a spread plate technique and reported as colony-forming units (CFU) per mL of effluent. The experiment was repeated 3 times with 2 days interval to estimate a change in the bacterial removal capacity of biofilters with an increase in exposure to contaminated stormwater.

2.8. Data and statistical analysis

The cumulative amount of biochar particles released during a rainfall event from a column was estimated based on the following equation: $m_{BC} = \sum_i C_i V_i$, where C_i and V_i are the concentration of biochar particles and volume of a sample fraction and i is the total number of sample fractions collected during a rainfall event. The log-removal of *E. coli* from stormwater during the attachment phase was calculated using the equation: log removal or removal capacity = − log (C/C_0), where C is the steady-state effluent concentration and C_0 is the influent concentration.

Statistical tests (one-way analysis of variance, ANOVA) were conducted to identify the differences between parameters measured under different experimental conditions. The significance of differences between two specific means was assessed with Tukey HSD post-hoc comparison test. Differences were considered significant at p-value < 0.05. All statistical analyses were performed using the computing environment R, version 3.6.1.

3. Results

3.1. Compaction conditions affected hydraulic conductivity

Compaction decreased the hydraulic conductivity of biofilter, but the extent to which the hydraulic conductivity decreased depended on media type and the presence of water (Fig. 1). All compacted columns had significantly ($p < 0.005$) lower hydraulic conductivity than the uncompacted biochar columns. Compaction of biochar under dry condition lowered the hydraulic conductivity by 44%. Compaction of biochar in wet condition (15% moisture) decreased the hydraulic conductivity by only 12% of the uncompacted biochar. Compaction decreased the hydraulic conductivity of biochar columns to a greater extent than compost columns. An addition of biochar to compost columns did not significantly ($p = 0.99$) changed their hydraulic conductivity.

3.2. Compaction increased water-holding capacity and macropore-matrix interaction

Effective pore volume, estimated from bromide breakthrough curves in unsaturated biofilters, provides a quantitative estimate of the fraction of total biofilter media exposed to contaminated stormwater during infiltration events (Fig. 2-A). The effective pore volume of uncompacted

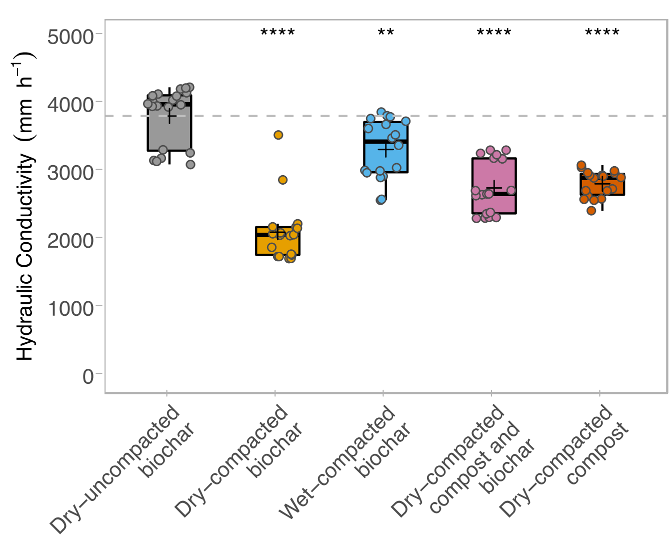

Fig. 1. Effect of compaction on saturated hydraulic conductivity of biofilter packed with a mixture of sand and adsorbent (15% by volume) including biochar and compost. The vertical dashed line indicates the mean hydraulic conductivity of uncompacted biochar columns. Plus (+) signs indicate mean hydraulic conductivity of total 18 measurements between triplicate columns of each type. Hydraulic conductivities of compacted columns were significantly lower than that of the uncompacted columns. A p-value of 0.01 and 0 correspond to notation "**" and "****", respectively.

biochar and wet-compacted biochar were similar, which was significantly ($p < 0.05$) lower than that of dry-compacted biochar columns (Fig. 2-B). It should be noted that the effective pore volume estimated from bromide breakthrough curves includes the volume of water in the drainage layer. Flow interruption during breakthrough tail increased the bromide concentration by a factor of 3 to 15 depending on the compaction conditions or media type (Fig. 2-B). The increase in bromide concentration was more apparent in compacted columns than the uncompacted columns.

3.3. Compaction conditions affected the quantity of particles released

During the infiltration of stormwater after compaction, particles were released in the effluent, but the concentration and total quantity of released particles depended on the media type and compaction conditions (Fig. 3). One of the concerns of compacting biochar is that biochar may break into smaller particles, which can be flushed out of the biofilter, thereby decreasing the concentration of biochar remained in the biofilter for intended application. However, we found that the total amount of particles released from each column were insignificant compared to the total amount of amendment (biochar or compost) added in the column. During each infiltration event, particle concentration peaked initially, but the particle concentration rapidly decreased with the passage of more stormwater. The peak in particle concentration decreased with successive rainfall events. The cumulative mass of particles released varied with column types. Among columns without compost, dry-compacted biochar columns released the least amount of biochar particles. The particle release potential in biochar columns increased with the following design conditions: dry compaction < no compaction < wet compaction. After dry compaction, compacted compost released more particles than compacted biochar.

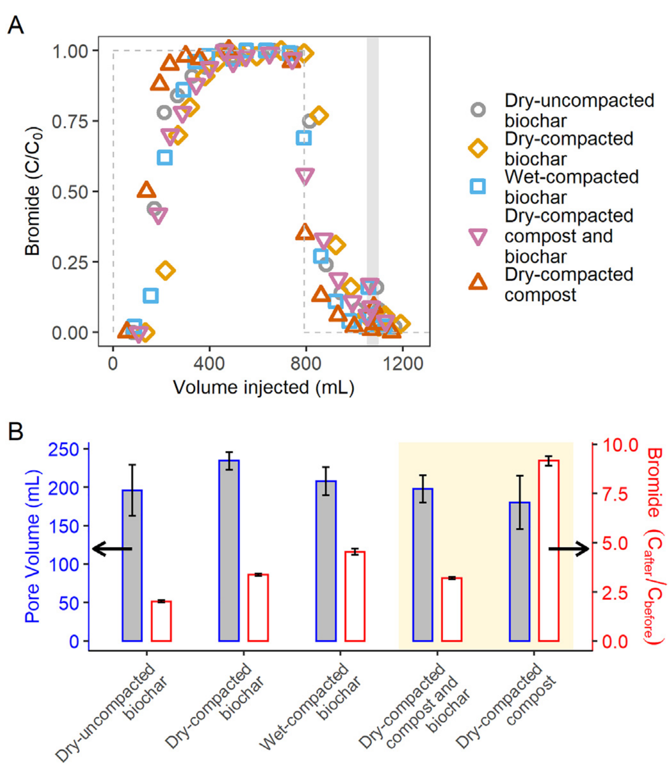

Fig. 2. (A) Breakthrough curves of bromide through columns packed with uncompacted biochar, compacted biochar under dry condition, compacted biochar under wet condition, compacted compost, and compacted compost and biochar mixture. The arrow mark indicates flow interruption for 12 h. (B) Effective pore volume, which is estimated based on the volume of stormwater injected to achieve 50% of bromide breakthrough ($C/C_0 = 0.5$) and increase in bromide concentration as a result of flow interruption, an indicator of diffusion dominated region in all columns. Error bars indicate one standard deviation over mean between triplicate columns.

Millions of particles (>99% are smaller than 3 μm) were present in the effluent, and the number of particles was higher in the columns with compost than the columns with biochar (Fig. 4-A). The size distribution of particles in the effluent was slightly different based on the compaction conditions and types of filter media used (Fig. 4-B). The particle size corresponding to peak distribution was smaller for biochar columns than for compost columns. The compaction conditions did not significantly ($p = 0.13$) affect the concentration of biochar particles released, but it affected the particle size distribution: the wet compacted biochar columns released a greater number of large particles than dry compacted columns. Columns with biochar released significantly fewer particles than the column with compost, indicating biochar is less susceptible to physical loss than compost under compaction. An addition of 15% (by volume) of biochar to compost columns significantly ($p < 0.05$) decreased the number of particles released and shifted the peak of the particle size distribution towards a smaller particle size, indicating that biochar can lower the loss of compost particles and block large particles. A decrease in particle released by replacing 15% of sand with biochar in compost-sand column is significant because sand has high load-bearing capacity than biochar and thus is expected to release less particles under compaction than biochar.

3.4. Compaction conditions affected *E. coli* removal

Compaction increased *E. coli* removal in biochar columns but the increase in removal depended on compaction conditions and the volume of contaminated stormwater injected (Fig. 5). During the first infiltration event, compacted biochar columns removed more *E. coli* than uncompacted biochar columns, and wet-compacted biochar columns removed more *E. coli* than dry-compacted biochar columns. However, increases in the exposure of contaminated water in the successive rainfall events reduced the *E. coli* removal capacity of all columns. After the exposure to 20 pore volumes of contaminated stormwater, the *E. coli* removal capacity of wet-compacted biochar columns (95 ± 02%) remained significantly ($p < 0.05$) greater than the removal capacity of dry-compacted (75 ± 06%) or uncompacted biochar columns (70 ± 10%), indicating wet compaction favors *E. coli* removal. The *E. coli* removal by dry-compacted compost columns was similar to the removal by dry-compacted biochar columns, and the addition of biochar to compost did not improve bacterial removal under the tested conditions. It should be noted that sand has significantly lower removal capacity than biochar (Mohanty and Boehm, 2014b; Mohanty et al., 2014); thus, amount of sand is not expected to influence the overall capacity of biochar-augmented columns.

4. Discussion

4.1. Cause of decrease in hydraulic conductivity of biochar after compaction

A decrease in saturated hydraulic conductivity of biofilters after compaction confirmed that compaction reduced the flow path permeability. The negative effect of compaction on hydraulic conductivity of biochar and sand mixture was more severe when the media was packed dry. This result confirmed that the presence of water in the filter media during compaction could reduce the negative impact of compaction on hydraulic conductivity. As water is an incompressible fluid, the presence of water in pores prevented compression of pore space. It should be noted that water content (15% by weight) used in this study can be nearly the field capacity of the mixture. At lower water contents, the presence of water could decrease friction between soil grains and increase compaction (Rollins et al., 1998). Thus, optimum moisture content for compaction could vary with filter media types and particle size distribution of filter media (Henderson et al., 2005). Future studies should determine the optimum water content for compaction of

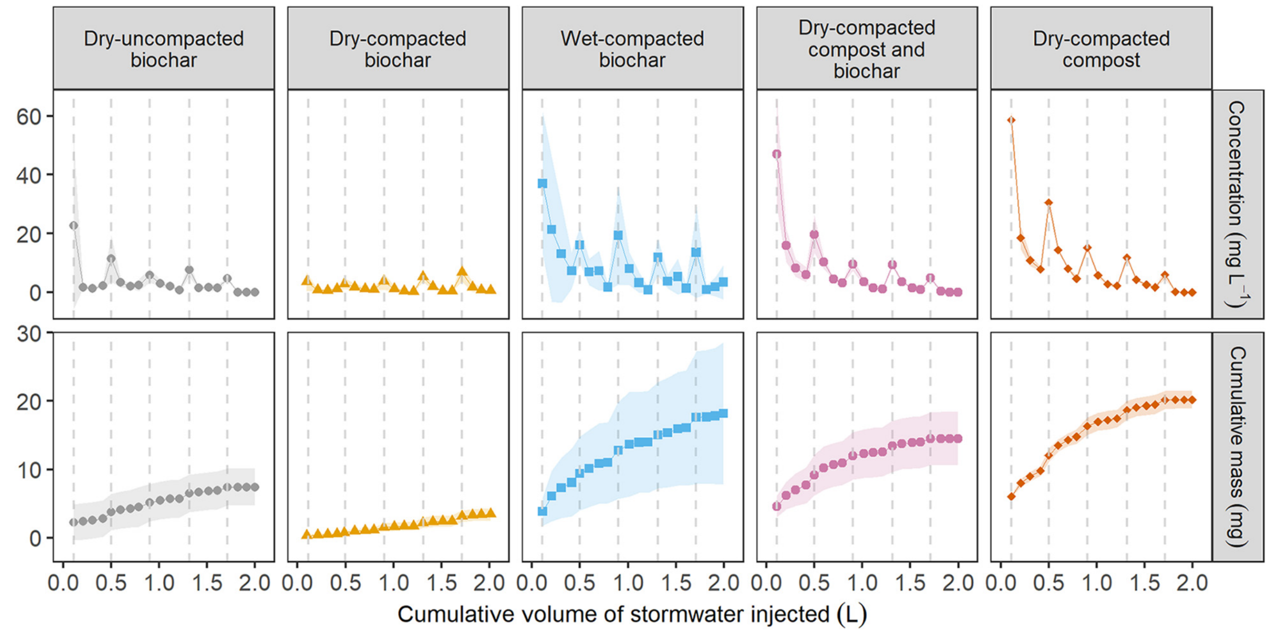

Fig. 3. Concentration (top) and cumulative mass (bottom) of particles released from biofilters packed with biochar or compost under different compaction conditions. Dashed lines indicate the start of rainfall infiltration events. Shaded area indicates one standard deviation over mean value from triplicate columns.

biochar-augmented soil or filter media. Compaction is expected to reduce the pore space between soil grains and decrease the flow path permeability (Gregory et al., 2006), which in turn could affect transport and removal of contaminants through biofilters (Hatt et al., 2008). Our results showed the extent to which flow paths could change after compaction of biofilter media.

Comparing the hydraulic conductivity of columns containing compacted biochar and compost, we showed that the hydraulic conductivity of biochar decreased to a greater extent than that of compost after compaction. We attribute this to low mechanical strength of biochar compared with compost. Biochar is produced by pyrolysis of biomass, which alters its physical properties and decreases its mechanical strength (Reza et al., 2012). Under stress, biochar could break and produce fine particles, which can further clog the constricted flow paths under compaction. Thus, biochar is less effective compared to compost in mitigating the impact of compaction on hydraulic conductivity. However, biochar offers a better contaminant removal capacity than compost. Thus, when high hydraulic conductivity of biofilter is desired, biochar should be mixed with compost to withstand the impact of compaction and to maintain both high infiltration and contaminant removal capacity.

4.2. Compaction increased stormwater interaction with filter media

Although biofilters are designed to quickly infiltrate stormwater, a high infiltration rate provides limited opportunity for contaminants to interact with the filter media, which consequently lowers the overall contaminant removal capacity of biofilters (Mohanty and Boehm, 2014a). Thus, conditions that could increase the interaction time without decreasing the infiltration capacity of biofilters could serve both purposes: reducing the quantity of runoff over land and contaminants in the effluent. Based on the bromide breakthrough time and exchange

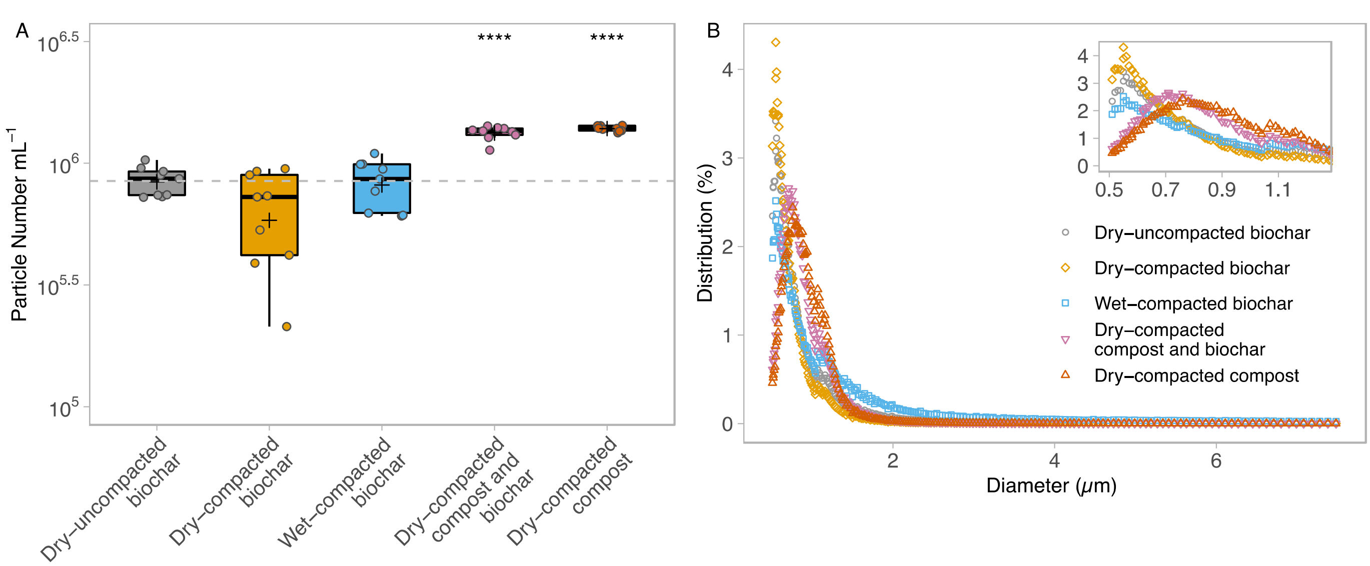

Fig. 4. (A) Concentration of particles (number per mL) in the first sample during the infiltration event, and (B) the size distribution of the particles. The insert shows the peak in particle size distribution curves.

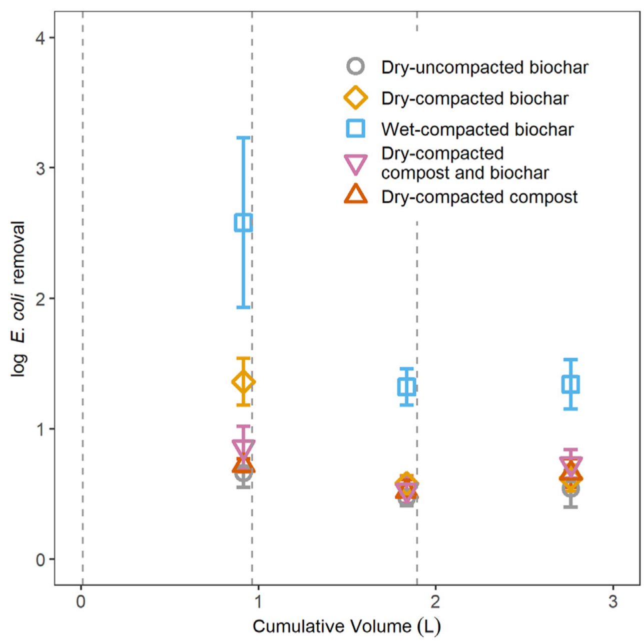

Fig. 5. Average *E. coli* removal by columns packed with a mixture of biochar or compost under different compaction conditions. Dashed lines indicate the start of a rainfall event, where >5 pore volume of contaminated stormwater was injected through the columns. Error bars indicate one standard deviation over mean log *E. coli* removal by triplicate columns of each type.

of bromide between macropores and micropores during flow interruption, we showed that compaction could increase the interaction of stormwater with filter media. Effective pore volume, a measure of the fraction of filter media exposed to stormwater during an infiltration event, was slightly higher in compacted biochar columns than that of uncompacted biochar columns.

Based on bromide concentration change after flow interruption, we showed that compaction increased the solute interaction between diffusion-limited regions and the flow paths. Diffusion-limited regions are comprised of intraparticle pores, micropores, capillary gaps between grains, and water film on the surface of biochar particles (Kumari et al., 2014). These regions are critical in the removal of contaminants in stormwater biofilters (Ulrich et al., 2015). Our study showed that compaction can disintegrate biochar and produce small particles, which could occupy pores between sands. This process could increase the volume of diffusion-limited regions. A decrease in hydraulic conductivity after compaction further increased the water-holding capacity, similar to how it was observed in another study that used natural soil (Peake et al., 2014). Thus, compaction increased the retention time of water in biofilters, which could help improve contaminant removal from stormwater. Compaction of soils could increase infiltration through preferential flow paths (Etana et al., 2013). Sands were used in this study, which cannot be compacted to the extent that it would block water entirely. Because sand has higher hydraulic conductivity than the rainfall application rate, stormwater is expected to move through preferential flow paths in unsaturated columns. Adding biochar and compaction could minimize the preferential flow paths by blocking the large pores.

4.3. Mechanism of particle release after compaction

Filter media serves a critical role in removing the contaminants from stormwater. However, intermittent infiltration of stormwater can release particles from filter media (Mohanty and Boehm, 2015), which has consequences on the loss of filter media and particle-facilitated leaching of contaminants in biofilter (Mohanty et al., 2013). Our results revealed that compaction could affect the quantity of particles available for mobilization during infiltration of stormwater, although pools of particles available depletes with successive infiltration events due to the exhaustion of particles generated during compaction. A fewer amount of biochar particles was released from dry-compacted columns than the wet-compacted columns. Based on the results, biochar release after compaction can be explained by a three-step process: (1) generation of particle by compaction, (2) diffusion of particles from grain wall to bulk liquid in flow paths, and (3) advective transport of broken biochar particles in flow paths where they can be removed by filtration or straining (Fig. 6). First, compaction can generate a high concentration of biochar particles due to the disintegration of biochar under pressure exerted during compaction. Increases in the percentage of particles smaller than 100 μm after compaction confirmed that compaction disintegrated biochar particles and produce smaller particles and increased the pool of particles in the biofilter (Fig. S3). Thus, the source is not a limiting factor for the release of particles. Second, during infiltration events, the suspended particles in pore paths were quickly eluted, which contributes to the initial peak. A rapid decrease in particle concentration indicates that a limited supply of particles to pore paths during infiltration. A linear relationship between cumulative particle released during a rainfall event as a function of the square root of time (Jacobsen et al., 1997) suggested that diffusion is a limiting step in the mobilization of biochar particles from grain walls to bulk liquid in flow paths (Fig. S4). A difference in leaching of particles in dry- and wet-compacted biochar columns indicates that the presence of water during compaction could help mobilization and transport of biochar particles. As the extent of diffusive transport would increase with the increase in water-filled pores, more biochar particles were mobilized in wet-compacted biochar, thereby increasing the availability of biochar particles for transport in flow paths. Third, the filtration of large biochar particles in narrow flow paths, which may be constricted during compaction, can limit the leaching of biochar particles.

We used hydraulic conductivity as a proxy measurement for flow path permeability. Higher hydraulic conductivity of wet-compacted biochar columns than that of dry-compacted biochar columns suggests that wet compacted biochar columns were more conducive to transport biochar particles. Consequently, a decrease in flow-path permeability in dry-compacted biochar columns resulted in a decrease in particle leaching. For the same reason, columns with compost leached more particles than biochar-only columns. These results confirmed that particle release processes after compaction is dominated by a transport-limited process, not a source-limited condition, and the transport of particles was dependent on the diffusion of particles from grain walls to bulk water in flow paths and physical filtration of particles when flow path width is smaller than particle size. As filter media containing wet-compacted biochar maintained a higher infiltration and *E. coli* removal capacity than the biofilter containing dry-compacted biochar, water should be added to biochar during compaction so that it maintains high hydraulic conductivity. The addition of water would also minimize the dust emission (Ravi et al., 2016) during installation. Biochar can also be mixed with compost to increase the hydraulic conductivity of the mixture.

4.4. Compaction conditions could affect E. coli removal

Our results showed that compaction of biochar improved *E. coli* removal during the first injection (clean bed), but repeated exposure of contaminated stormwater decreased removal of *E. coli*. We attributed the initial high removal in columns with compacted biochar compared to uncompacted biochar to fragmentation of biochar particles during compaction that expose additional surface areas for bacterial attachment and to increase in straining or physical filtration (Sasidharan et al., 2016) by pore clogged with fragmented biochar particles. Furthermore, compaction altered pore paths and decreased the pore space, which in turns increased the interaction *E. coli* in infiltrating stormwater with biochar, resulting increased removal. In our study, bacterial

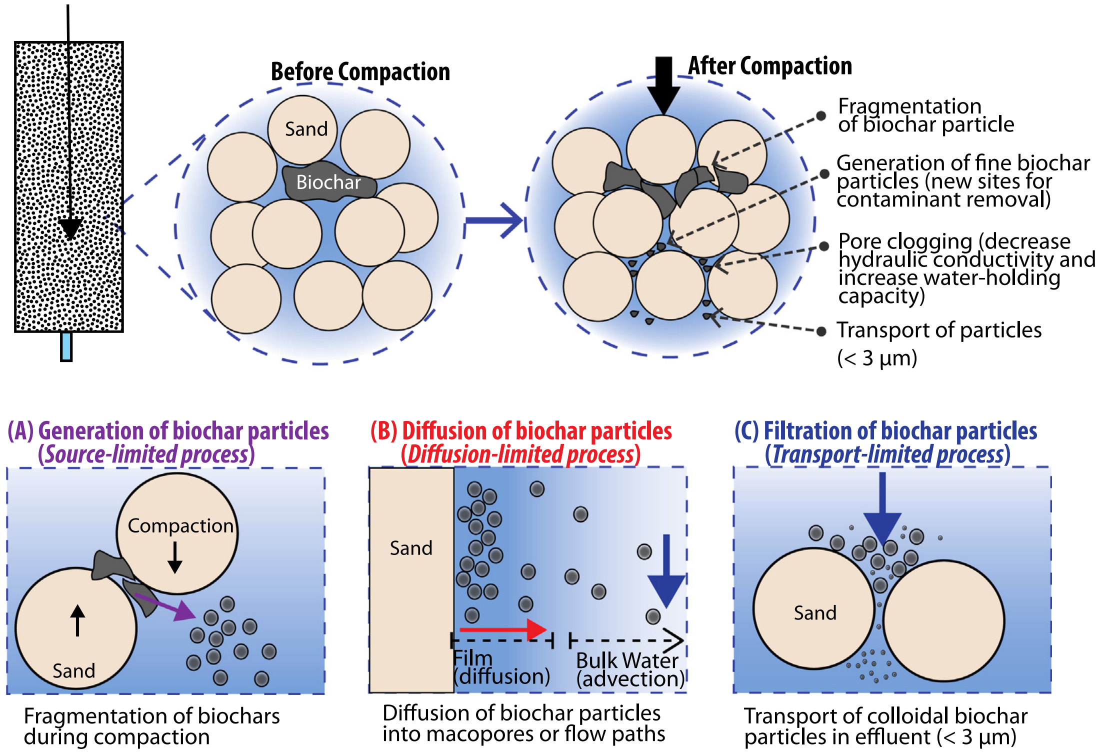

Fig. 6. Suggested mechanisms of biochar particle release due to compaction. First, compaction causes disintegration of biochar particles, which generates fine biochar particles and decreases average biochar particle size in sand filter. Second, fine biochar particles deposited on grain surfaces diffuse from the film surrounding particles to bulk water in flow paths, which limits the amount of biochar particles available for transport during an infiltration event. Third, only a fraction of total available biochar particles based on size (<3 μm) could transport as the pore path width, which may become constricted during compaction, can limit the transport or leaching of biochar particles during infiltration events.

removal decreased with increases in the exposure of contaminated stormwater, which indicates that the attachment sites on particles generated after compaction were exhausted progressively. This is similar to observation in another field study with biochar, where the removal capacity decreased after initial high removal (Kranner et al., 2019).

Removal in wet-compacted biochar was more than that in dry-compacted biochar, which indicates that *E. coli* interaction with biochar was greater in the wet-compacted column than the dry-compacted columns. Based on bromide breakthrough data, pore-water connectivity was higher in wet-compacted biochar columns compared with dry-compacted biochar columns, indicating a greater fraction of wet-compacted biochar columns was in contact with *E. coli* in infiltrating stormwater. Overall, these results indicate that compacting biochar in the presence of water may increase *E. coli* removal in biofilters. It should be noted that road runoff typically contains high concentration of dissolved pollutants such as heavy metals and organic pollutants. Our result show that compaction can affect pore-water interaction with filter media and water retention in biofilter, which could change the geochemical and redox properties of pore water. As geochemical and redox properties are critical in removal of dissolved pollutants, future studies should examine the mechanistic link between compaction and removal of dissolved pollutant in roadside biofilters.

5. Conclusions

We examine the effect of compaction on physical processes of stormwater treatment including stormwater infiltration, particle release, and removal of particulate pollutants such as *E. coli*, and provide a mechanistic understanding of how compaction condition such as presence of moisture could affect the performance of roadside soil augmented with biochar. The results can inform the design guideline for the construction of roadside biofilters with biochar as an amendment. Specific conclusions are:

- Compaction decreased hydraulic conductivity of biochar-augmented biofilter, but the detrimental effect of compaction can be minimized by adding compost and water.
- Compaction disintegrated biochar particles, which can be released during intermittent infiltration of stormwater. Although compactions generated fine biochar particles, the net release of these particles was controlled by the flow-path permeability after compaction.
- Irrespective of the initial release of biochar particles after compaction, the total biochar amount released is insignificant compared to the total biochar remained in the system, and the extent of biochar release was less than that observed in compost columns.
- Compaction increased water holding capacity and interaction time of stormwater with filter media.
- Compaction increased *E. coli* removal in a short term but the benefit was short-lived in dry-compacted biofilters augmented with biochar. Wet-compacted biofilter consistently removes more *E. coli* than dry-compacted or uncompacted biofilter with biochar.

CRediT authorship contribution statement

Maryam Ghavanloughajar: Methodology, Writing - original draft. **Renan Valenca:** Writing - review & editing, Visualization, Formal analysis. **Huong Le:** Methodology, Writing - original draft. **Merrick Rahman:** Methodology. **Annesh Borthakur:** Methodology, Formal analysis. **Sujith Ravi:** Writing - review & editing. **Michael K. Stenstrom:** Writing - review & editing. **Sanjay K. Mohanty:** Conceptualization, Funding acquisition, Writing - review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data contains detail description of packing method and water sample analysis, properties of biochar (Table S1), a schematic of the experimental setup (Fig. S1), bulk density of different layer during packing (Fig. S2), the particle size distribution of sand-biochar mixture before and after compaction (Fig. S3), and cumulative particle released as a function of the square root of time of infiltration (Fig. S4) to prove diffusive transport of broken biochar particles to flow paths. Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.139180.

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