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Authors
Das, Tonoy K
Raoelison, Onja D
Rehman, Hamid
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Use of expanded shale, clay, and slate aggregates and biochar in the clear zone of road infrastructures for sustainable treatment of stormwater

Tonoy K. Das [a], Onja D. Raoelison [a], Hamid Rehman [a,b], Yuhui Zhang [a], Wendy Chau [a], Lisa Thamiz [a], Michael K. Stenstrom [a], Sanjay K. Mohanty [a,*]

[a] Department of Civil and Environmental Engineering, University of California Los Angeles, USA
[b] Department of Environmental Sciences, Quaid-i-Azam University, Islamabad, Pakistan

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ABSTRACT

A Clear Zone (CZ), the unobstructed roadside area with highly compacted soil, naturally accumulates high concentrations of pollutants from traffic activities. These pollutants are washed off by road runoff and enter waterways. In situ, treatment of polluted runoff from the CZ could not only protect water resources but also provide an opportunity to recharge groundwater. However, the soil in the CZ requires compaction, which limits the natural infiltration and treatment of road runoff. In this study, we examine whether and how amending the soil in the CZ with sand, a common bulking agent used in road design, and Expanded Shale, Clay, and Slate (ESCS) aggregates, a novel light-weight engineered bulking agent, could help treat stormwater in situ. ESCS-amended soil media infiltrated 220% more water than sand-amended soil under compaction, indicating that the addition of ESCS would make the CZ better at treating road runoff generated during high-intensity rainfall. Compared to sand-amended soil in the CZ, ESCS-amended soil provided 58% more plant-available water during prolonged drying, indicating that ESCS addition would help maintain vegetation, thereby minimizing maintenance needs. Finally, replacing sand with ESCS improved the soil capacity in the CZ to remove pollutants, including heavy metals and *E. coli*, indicating the performance life of ESCS-amended soil would be longer than that of sand-amended soil in the CZ. Collectively, these results indicate that the addition of ESCS as an alternative bulking agent to sand in compacted soil in the CZ could potentially treat road runoff in situ and prevent pollution originating from road infrastructure.

1. Introduction

Ensuring a consistent and sustainable water supply for the rapidly growing urban areas, where nearly 70% of the global population will be living by 2050, poses a formidable challenge (Ahmadi et al., 2020; He et al., 2021). Most urban areas are located in places that have been facing severe water scarcity (He et al., 2021). Ironically, urbanization also limits local water supply because the impervious surfaces or compacted soils created during land development, such as road infrastructure, increase runoff and limit the natural recharge of groundwater (Epps and Hathaway, 2021; McGrane, 2016). During urban development, a large fraction of space is occupied by road infrastructure, which not only limits infiltration but also helps generate pollutants during traffic activities. Most road runoff contains high concentrations of metals, oils, and pathogens (Han et al., 2006). During rainfall, all these pollutants are washed off by road runoff and conveyed to nearby waterbodies. In the 2017 National Water Quality Inventory Report by the US EPA, road runoff is found to be a significant source of water quality impairments in surface waters throughout the US (USEPA, 2017). State highway agencies are required to comply with the US National Pollution Discharge Elimination permit, including the infiltration of stormwater runoff from the highway and implementing soil-based stormwater best management practices (USEPA, 2021). Thus, treatment of road runoff in situ could provide an opportunity to mitigate this long-standing water quality issue.

In situ treatment of road runoff is challenging because the road design guideline permits limited infiltration of stormwater on the roadside in a Clear Zone (CZ). The US Federal Highway Administration has defined a Clear Zone as “an unobstructed, traversable roadside area that allows a driver to stop safely, or regain control of a vehicle that has left the roadway”. The width of the clear zone is typically 3–15 m based on the risk determined by the speed limit, the slope of the terrain, and

* Corresponding author. University of California Los Angeles, Civil and Environmental Engineering, 420 Westwood Plaza, Los Angeles, CA, 90095, USA.
E-mail addresses: tdas@ucla.edu (T.K. Das), mohanty@ucla.edu (S.K. Mohanty).

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the volume of traffic (Transportation Officials Task Force for Roadside Safety, 2011). Thus, for 100 km of road, the CZ on both sides of the road could take between 0.6 and 3 km^2 of space. Transforming this space into green infrastructure or stormwater treatment systems could decrease pollutant loading from road runoff. However, the soil within a CZ is required to be compacted to 85–90% of its capacity to meet the design criteria for road infrastructure construction (Goenaga et al., 2023; Transportation Officials Task Force for Roadside Safety, 2011). Compaction leads to an impermeable surface, which decreases natural infiltration and increases the volume and speed of surface runoff. Thus, adding amendments to alleviate the effect of compaction on infiltration could potentially turn the Clear Zone into a network of stormwater treatment solutions.

Sand is typically used to enhance stormwater infiltration and to alleviate the negative effects of compaction in roadside soil (Bean and Dukes, 2015; Fassman-Beck et al., 2015). For stormwater treatment systems installed outside the perimeter of the CZ, 60–70% sand is typically used as a bulking agent to increase the infiltration capacity (California Department of Transportation, 2021; Das et al., 2023b; Tirpak et al., 2021). Sand is also an ideal bulking agent to alleviate the negative impact of compaction in roadside soil (Das et al., 2023a, 2023b; Sileshi et al., 2012). Despite the positive effect of sand on aiding infiltration, their use in high amounts in the roadside soil could pose two issues. First, sand has a limited capacity to adsorb pollutants, thereby requiring the use of other amendments, such as biochar (Mohanty et al., 2018). Road runoff particularly contains high concentrations of pollutants (Han et al., 2006), such as metals, pathogens, and organics, which can exhaust the adsorption capacity of soil containing high amounts of sand. Second, the soil media with high amounts of sand has a low water-holding capacity for plants, thereby making it challenging to maintain vegetation during dry climates (Schaller et al., 2020). This issue will be severe during climate change when the drying duration is projected to increase (Grant et al., 2013; Weathers et al., 2023). Vegetation use is necessary on roadside subsoil because it serves many functions in addition to reducing roadside soil erosion or structure erosion (Muerdter et al., 2018). Therefore, it is critical to find an alternative bulking agent for roadside soil that could meet three criteria: (1) it should infiltrate water despite compaction; (2) it should hold water longer after rainfall for plant use; (3) it should remove pollutants.

Expanded Shale, Clay, and Slate (ESCS) aggregates could be an alternative bulking agent that could meet these criteria and improve the desired hydraulic and pollutant removal functions of roadside soil. For instance, a recent study found that replacing sand with ESCS in rain gardens may increase plant life survival rates beyond rates currently observed in high sand-content rain gardens (Funai and Kupec, 2019). Another study found that ESCS could adsorb high amounts of metals as well as *E. coli* from polluted runoff, and their bacterial removal capacity could only increase with their aging (Borthakur et al., 2022a). Other studies demonstrated ESCS capacity for a wide range of stormwater pollutants (Dordio and Carvalho, 2013; Kalhori et al., 2013a; Malakootian et al., 2009; Nkansah et al., 2012). However, the previous studies rarely tested ESCS infiltration capacity under compaction. Unlike sand, ESCS is made out of clay or shale aggregate, which may crumble under compaction pressure if the aggregate's strength is insufficient to withstand compaction force. Furthermore, its water-holding capacity is rarely measured. Thus, it is critical to test whether ESCS can be a better alternative to sand to meet the design and performance criteria of roadside stormwater infrastructure.

The objective of this study is to compare the ability of soil in the CZ amended with ESCS aggregates and sand to infiltrate runoff during heavy rainfall, hold water for plants during drought, and remove *E. coli* and heavy metals from stormwater. To achieve the objective, soil collected from the roadside was mixed with sand or ESCS as a bulking agent and biochar as a reactive amendment for pollutant removal and compacted in columns to test their infiltration and pollutant removal capacities. Comparing hydraulic and pollutant removal behavior during simulated heavy rainfall and drought, we show that ESCS could have the potential to increase the resilience of amended soil in the CZ during changing climates.

2. Material and methods

2.1. Stormwater preparation

For all experiments, natural stormwater was used, which was collected from Ballona Creek in Los Angeles, CA (34° 00′32″ N, 118° 23′3″ W). The creek receives dry-weather irrigation runoff from 318 km^2 of the urban area, with 82% developed and 61% impervious surface. The detailed characteristics of stormwater from the sampling area were reported elsewhere (Borthakur et al., 2022b; Ghavanloughajar et al., 2021). The specific water quality parameters for the samples used in this study are detailed in Table S1. Within 1 h of sample collection, the pH and conductivity of the stormwater were measured using a meter connected to an ion-selective electrode (Model #9107BN, Fisher Scientific) and conductivity probe (Two-Cell Accumet, Fisher Scientific), respectively. The stormwater sample was stored at 4 °C until its use in the experiment.

The stormwater was spiked with pollutants to examine their removal in amended soil media. We tested the capacity of compacted soil mixed with sand or ESCS to remove *E. coli* and heavy metals. These two classes of pollutants are chosen as they are often the leading cause of total maximum daily load (TMDL) violations in road run-off in urban areas (USEPA, 2017; Vogel and Moore, 2016). As dissolved metal can be toxic to *E. coli* (Borthakur et al., 2022a), stormwater spiked with *E. coli* was first used to estimate the *E. coli* removal capacity of media mixtures before repeating the same procedure with stormwater spiked with heavy metals to estimate the metal removal capacity of the media mixture. The collected stormwater was first autoclaved to kill native microorganisms and spiked with a kanamycin-resistant strain of *Escherichia coli* K12 to make the final mean concentration of *E. coli* in the influent to $3.4 \pm 0.4 \times 10^5$ CFU mL^{-1} (Valenca et al., 2020). To prepare the stormwater contaminated with metals, natural stormwater was spiked with the most common metals found in road runoff in Los Angeles, which included Pb, Zn, Ni, Cd, Co, Cu, and Cr so that the final concentration of each metal would be 100 μg L^{-1} (Ferreira et al., 2013). The concentration is within the range found in highly polluted urban runoff (Grebel et al., 2013).

2.2. Collection of soil samples

The soil sample is collected from a location (34° 01′59″ N, 118° 13′48″ W) within CZ of a freeway in Los Angeles County, USA. Topsoil was cleared of mulch and plant roots at four random spots. The soil was collected from a subsurface layer up to 45 cm deep from multiple random spots within the CZ using a shovel. Soil from all spots was mixed uniformly to create a composite soil sample. The soil was air-dried in the room at 20–23 °C to <10% moisture and sieved to remove gravel (>2 mm) before use. Thus, the microbial community in the soil is not destroyed during the drying process, although the microbial activity is expected to decrease with a decrease in moisture content. Some of the relevant physical properties of soil were reported in Table S2.

2.3. Preparation of soil and bulking media mixture

To simulate infiltration and treatment of stormwater in amendment soil, we designed a media filter without vegetation using laboratory columns (Ghavanloughajar et al., 2020). A typical infiltration-based stormwater system is designed by mixing native soil with sand as a bulking agent and occasionally with engineered media such as biochar to improve pollutant removal (Tirpak et al., 2021). Here, we used three types of amendments to mix with soil from the CZ: sand, ESCS, and biochar. While sand and ESCS serve as bulking agents to enhance infiltration in compacted soil, biochar is used to increase pollutant capture from infiltrating road runoff. Sand is typically used to enhance the infiltration and alleviate the negative impact of compaction, but it doesn't offer additional capacity to adsorb most dissolved pollutants (Tirpak et al., 2021). In contrast, ESCS aggregate can provide the function of the bulking agent while removing dissolved and particulate pollutants from contaminated runoff (Borthakur et al., 2022a). Here, we tested ESCS aggregates (ARCOSA Lightweight, USA) as an alternative bulking agent for sand to improve the hydraulic performance of soil in the CZ. We obtained commercially available biochar (Rogue biochar, Oregon Biochar, OR) and coarse sand (ASTM 20–30, Humboldt Mfg Co.) and used them without any other modification or pretreatment. The coarse sand (600–850 μm) was washed in de-ionized (DI) water to remove silica colloids and dried at 105 °C overnight. The biochar, which was produced by the gasification of softwood at 900–1000 °C, has been previously tested for its use in compacted media filters (Ghavanloughajar et al., 2020). Biochar and ESCS were sieved (mesh #10) to remove particles larger than 2 mm to minimize the formation of preferential flow paths in the packed media. We mixed sand (75% by volume) with soil (25% by volume) to represent conventional infiltration-based stormwater control measures (Tirpak et al., 2021). As the contaminant removal capacity of sand is minimal (Tirpak et al., 2021), 25% (by volume) of sand was replaced with biochar to enhance pollutant removal in the filter beds. Thus, the final composite mixture contains sand (50%), soil (25%), and biochar (25%) by volume. To compare the utility of ESCS as an alternative bulking agent of sand, another composite mixture was created using ESCS (50%), soil (25%), and biochar (25%).

2.4. Column setup to simulate stormwater capture in the clear zone

1-D transport experiment was conducted by packing the soil and amendment mixture in transparent PVC tubes (5.1 cm ID and 61.0 cm length) as described in a previous study (Ghavanloughajar et al., 2020). Briefly, the PVC tube was glued with PVC fittings and connected to a control valve to regulate the effluent flow. Three types of media mixture were packed in a total of 18 columns with or without compaction, where triplicate columns with and without compaction were used per media mixture: (1) sand and soil; (2) sand, soil, and biochar; (3) ESCS, soil, and biochar. To simulate the compaction of CZ soil during road construction, the media mixture was added incrementally in layers and compacted to a layer height of 3.8 cm 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 4 layers so that the total height of the media layer became 15.2 cm. The bulk density was calculated during each layer's compaction to ensure uniform filter media distribution (Fig. S1). After packing, the compacted soil media was characterized for porosity, pore volume (PV), and saturated hydraulic conductivity following methods described in a previous study (Le et al., 2020). The mixture composition of the soil columns and their hydraulic characteristics are summarized in Table S3.

2.5. Water retention behavior of amended soils in the clear zone

We compared the water-holding capacity of soil media during the natural drying of soil media following the method outlined elsewhere (Trifunovic et al., 2018). Briefly, the soil media mixture was repacked in empty 250 cm^3 ring cores to match the same bulk density of the compacted media layer in the model filter bed, and the soil water retention curve and the unsaturated hydraulic conductivity of treatments were measured using the HYPROP device (METER Group, Inc., USA). The HYPROP measures the unsaturated hydraulic conductivity based on the evaporation method by simultaneously recording the sample weight and soil matric potential during the sample drying cycle from saturation to around pF 2.5, where pF = $\log_{10}$ h and h is the suction in cm below the wilting point. We utilized the bimodal soil water retention model (Durner, 1994), which is ideal for describing changes in the physical properties of media having a heterogeneous pore structure. In this case, the water retention curve is expressed as a linear superposition of sub-curves of a homogeneous pore structure using an unimodal model (van Genuchten, 1980), and effective saturation was estimated using the equation below:

$$S_e = w_1\left[\frac{1}{1+(\alpha_1 h)^{n_1}}\right]^{m_1} + (1-w_1)\left[\frac{1}{1+(\alpha_2 h)^{n_2}}\right]^{m_2}$$

where S_e is effective saturation; w_1 is the weighing factor for the first sub curve subject to $0 < w_i < 1$; α is a scaling factor that determines the position of the pore size maximum; h is the suction (cm); n and m are empirical shape parameters and m =(1-1/n). S_e is related to volumetric water content as $\theta = \theta_r + (\theta_s - \theta_r)\, S_e$, where θ is the volumetric water content, θ_s is saturated water content, and θ_r is the residual water content ($cm^3\ cm^{-3}$). The model was implemented using a nonlinear fitting program (Seki, 2007), and the modeled water retention curve was fitted with experimental data using the derived parameters.

2.6. Testing pollutant removal capacity of amended compacted soil in the clear zone

To simulate natural rainfall events, soil media filters were subjected to intermittent infiltration of the contaminated stormwater followed by a drying event when the column was drained under gravity and left to dry at room temperature (22 °C). During the application of *E. coli*-spiked stormwater, 3 PV of stormwater was applied at a flux of 1 mL min^{-1} on the top of the media filters. This flux rate is lower than the minimum hydraulic conductivity of all media mixtures under compaction, ensuring stormwater would not on the top of the filter media during the injection. The effluent samples were collected in fractions from the bottom, but only the last 0.5 PV fraction of the samples were analyzed for *E. coli* concentration using a spread plate technique described elsewhere (Mohanty et al., 2013). The last 0.5 PV after injection of at least 3 PV of contaminated stormwater represents the steady-state concentration and has been used to estimate the removal capacity of the CZ soil amended with bulking agents (Mohanty et al., 2013). The removal capacities of different media mixtures were compared by estimating the log removal as - log (C/C_0), where C is the effluent concentration (C), and C_0 is the influent concentration. The intermittent injection of *E. coli*-spiked stormwater was repeated 5 times to estimate each configuration's mean bacterial removal capacity.

Following experiments with *E. coli*, a similar experiment was repeated with stormwater contaminated with heavy metals. Unlike bacteria that can break through within 3 PV of stormwater injection, metals can take a long time to appear in the effluent based on the metal adsorption capacity of the media mixture. A preliminary experiment indicates that the native CZ soil has a high capacity to adsorb metals. To ensure the metal breakthrough in the effluent, we applied approximately 700 PV of contaminated stormwater over 60 days and measured effluent metal concentration at specific time intervals. For the analysis of dissolved metals, effluent samples were centrifuged at 6120 G-force for 15 min to settle any suspended particles larger than 0.04 μm. The supernatant was acidified (pH ~3) using nitric acid and analyzed for heavy metals using an Inductively Coupled Plasma-Mass Spectroscopy (ICP-MS). The detection limit for heavy metals in ICP-MS is 1–10 μg L^{-1}. The metal removal capacity of soil media filters was calculated by using the equation: $1-(C_e/C_i)$; where C_e and C_i represent the concentration in the effluent and influent, respectively.

3. Results

3.1. Infiltration capacity of amended soils

Compaction reduced the hydraulic conductivity of all media mixtures (Fig. S2). Under compaction, the hydraulic conductivity of ESCS-amended soil and biochar mixture was higher than that of sand-amended soil and biochar mixture, indicating ESCS media is better than sand to alleviate the negative impact of compaction (Fig. 1). The mean hydraulic conductivity of compacted sand-soil media with 75% sand was 341 mm h^{-1} (Fig. 1). Adding biochar to the sand and soil mixture reduced their hydraulic conductivity significantly to 41 mm h^{-1}, which is below the desired design infiltration rate of 50–127 mm h^{-1} (California Department of Transportation, 2021). Replacing sand with ESCS as bulking media increased the hydraulic conductivity by 220% to 131 mm h^{-1} and met the design infiltration rate for stormwater media filters.

3.2. Water retention behaviors of amended soils

The plant-available water is a crucial parameter for vegetation performance under drought. An increase in drying duration increases water loss by evaporation from filter media pores, thereby increasing suction or negative pressure in the pores. At a given suction, corresponding to a specific drying duration, the ESCS-amended soil media retained more moisture than the sand-amended soil (Fig. 2). The water-holding capacity of the sand-soil mixture was the lowest, which increased with the addition of biochar (Table 1). Replacing sand with ESCS further increased the water-holding capacity by 58%.

3.3. Dissolved oxygen in pore water in amended soils

Compaction decreased dissolved oxygen (DO) concentration in pore water (Fig. S3). Under compaction, DO concentration in pore water in ESCS-amended soil media was higher than that in sand-amended soil media. Effluent pH and electrical conductivity from all columns remained consistent at 7.6 ± 0.1 and 1363 ± 24 μS cm^{-1}, respectively (Fig. 3).

3.4. Comparison of E-coli removal in amended soils

In uncompacted conditions, ESCS-amended soil media removed more *E. coli* than sand-amended soil (Fig. 3). Compaction appears to increase the average *E. coli* removal for both media mixtures, although the difference in removal between both media mixtures was insignificant. All media mixtures recorded >2 log removal irrespective of compaction, potentially because the soil had an unusually high capacity to adsorb *E. coli*. To assess the role of only soil, a sand-only filter media was tested which showed limited removal of 56%, but adding soil increased removal by 4 orders of magnitude, confirming the soil was either toxic to *E. coli* or had an unusually high capacity to adsorb *E. coli* (Fig. S4).

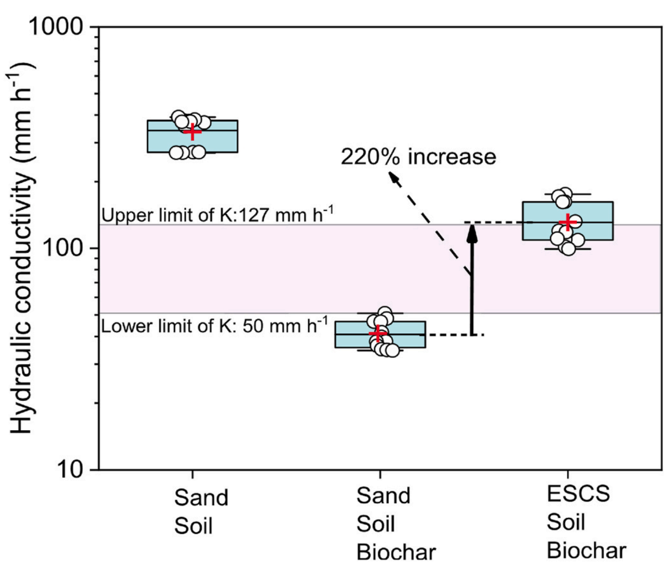

Fig. 1. Comparison of hydraulic conductivity of three soil media mixtures under compaction: sand (75% by volume) and soil (25%); sand (50%), soil (25%), and biochar (25%); ESCS (50%), soil (25%), and biochar (25%). The shaded area indicates the design hydraulic conductivity of the roadside soil. Plus (+) signs indicate the mean hydraulic conductivity of a total of 12 measurements in triplicate columns per media mixture type.

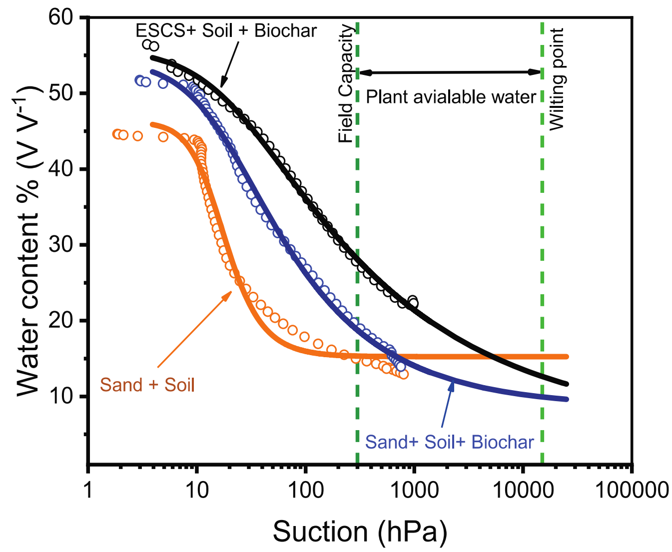

Fig. 2. Comparison of water retention behavior of three types of soil media mixtures. The solid lines indicate the van Genuchten (1980) unimodal fit for the experimental data. The plant-available water is the difference between the vertical dash lines of field capacity and the permanent wilting point.

3.5. Metal removal in amended soils

In general, the removal of metals decreased with increased exposure to metal-contaminated stormwater but the reduction was more prominent in the soil media mixture amended with sand than in the mixture amended with ESCS (Fig. S5). After the passage of 700 PV of contaminated stormwater, the soil media mixture amended with ESCS consistently adsorbed more metals than the mixture amended with sand (Fig. 4). At that point, the average removal for all metals in the sand column was 62.9 ± 8.5 %, which increased to 83.5 ± 4.9 % when sand was replaced with ESCS. The extent to which ESCS improved metal removal depended on metal types. Replacement of sand with ESCS increases the removal of Pb, Co, Ni, Cu, Zn, Cd, and Cr by 30.7%, 23.5%, 27.8%, 22.7%, 8.8%, 11.0%, and 19.6%, respectively.

4. Discussion

4.1. Cause of better hydraulic performance of ESCS than sand under compaction

The compaction of roadside soil limits their natural infiltration capacity, and the addition of sand and biochar could improve the capacity to some extent but not to the desired limit (~50–127 mm h^{-1}) to handle high flow rates during extreme rainfall events. Our results (Fig. 1) show that the addition of ESCS media could help the roadside soil mixture meet the desired infiltration threshold despite compaction. We attributed the results to the high aggregate size of ESCS. The ESCS has a larger grain size than sand, creating large macropores while packing columns (Chung et al., 2018). The macropore distribution creates a more connected flow path and enhances the infiltration rate in ESCS media

Table 1
Parameter of van Genuchten model from water retention curve.

Media mixture	θ_s	θ_r	$\theta_{pF\ 2.5\ (300\ hPa)}$	$\theta_{pF\ 4.2\ (15,000\ hPa)}$	PAW	α	n	K_s (mm.h^{-1})
Sand + soil	46.28	15.24	15.32	14.30	1.02	0.066	2.967	341
Sand + Soil + biochar	54.46	8.60	18.57	9.01	9.56	0.059	1.519	41
ESCS + soil + biochar	55.95	5.51	27.86	12.48	15.38	0.048	1.296	131

Θ_s: Saturated water content, θ_r Residual water content, $\theta_{pF\ 2.5}$ Field capacity, $\theta_{pF\ 4.2}$: Permanent wilting point, PAW: Plant available water, α: scaling factor, n: empirical shape parameter, K_s: saturated hydraulic conductivity.

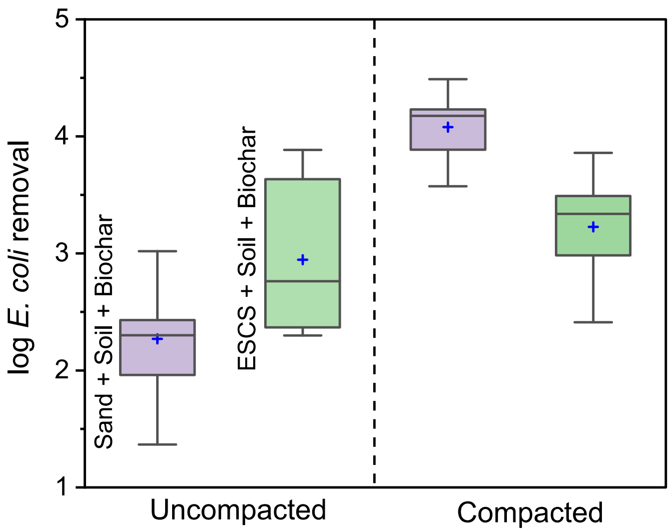

Fig. 3. The removal of *E. coli* by compacted and uncompacted soil-biochar media mixture amended with sand or ESCS.

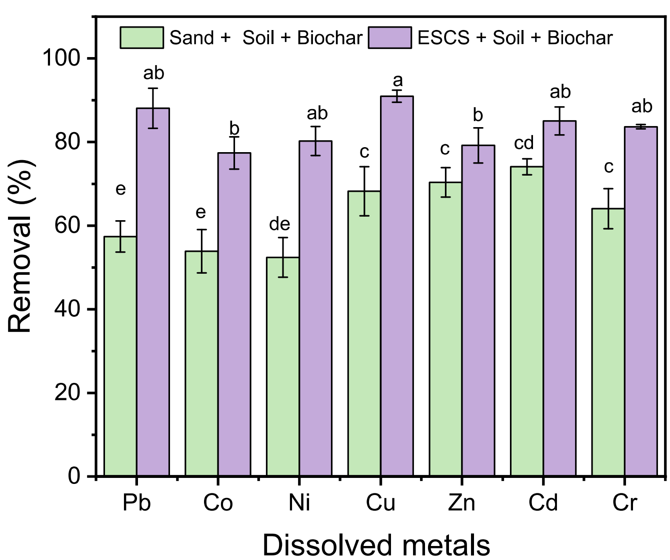

Fig. 4. The metal removal performance of ESCS amended soil media mixture after exposure of 700 PV metal contaminated natural stormwater. Error bars indicate one standard deviation over the mean based on the results from triplicate columns. Means that do not share a letter are significantly different.

(Chandel et al., 2022). Soil-water retention curves of all media mixtures in our study confirmed an increase in macro and mesoporosity of soil amended with ESCS (Fig. 2). Unlike other amendments such as biochar that can break under compaction pressure (Le et al., 2020), ESCS media appears to remain mostly intact under compaction due to its structural stability of aggregate created under high heat. Our results corroborated the results of other studies on ESCS without compaction that showed the addition of ESCS could increase the infiltration capacity of stormwater treatment systems (Funai and Kupec, 2019; Mechleb et al., 2014). Our study shows that the hydraulic conductivity of ESCS does not deteriorate as much as sand due to large aggregate and protected intraparticle pore space. As ESCS can be produced in any size, they can be tailored to specific aggregate sizes based on soil hydrological groups. The high infiltration capacity of ESCS-amended roadside soil is particularly beneficial to soak more water from high-speed runoff from the road surface. The enhanced infiltration could reduce flooding and increase groundwater recharge through dry well injection. Thus, adding ESCS amendments to thousands of square kilometers of unused space on CZ soil could transform them into multifunctional managed aquifer recharge facilities for water sustainability (Alam et al., 2021), which is otherwise not possible in the space-constraint urban landscape. However, the success of this design would depend on the infiltration of the capacity of the native soil beneath the road.

4.2. Cause of high plant-available water in ESCS-amended soil

Some of the clear zones could contain plants or grass by design to minimize erosion. However, maintaining vegetation in the clear zone could be challenging in dry climates due to poor water retention. Thus, adding an amendment that could retain water for a longer period after rainfall without limiting the infiltration capacity could alleviate the issue. Our result shows that ESCS retained more water than sand did during the drying period. ESCS exhibited higher water content at field capacity and higher plant available water than sand (Fig. 2 and Table 1). We attribute the result to the formation of mesopore during compaction. The pore space geometry, dimensions, and packing density affect water retention behavior in porous media (Zhai et al., 2020). Unlike solid sand, ESCS aggregates have internal micro and mesopores that stay intact despite compaction and contribute to water retention. During packing, ESCS likely created more inter particles of mesopores and macropores than the smaller sand particles. This could be one reason why ESCS had a more significant impact on water retention at field capacity (Liu et al., 2017). Moisture retained within the internal pore of ESCS can become available to the surrounding soil matrix as the roadside soil dries and supply water to the plant (Wang et al., 2019). Our result also explained why incorporating ESCS as a replacement for high sand content increased plant life survival rates during dry spells in rain gardens (Funai and Kupec, 2019). As climate change has increased extreme hydrological events such as prolonged drought, improving the water retention capacity of roadside soil or filter media in stormwater control measures by adding ESCS could support healthy vegetation establishment and microbial community and increase their climate resilience.

4.3. Cause of high E. coli removal in ESCS amended soil

E. coli is one of the most difficult pollutants to remove in stormwater control measures because of the low capacity of sand unless other amendments, such as biochar, drinking water treatment residues and iron filing, are added to improve the *E. coli* removal (Ghavanloughajar et al., 2021; Raoelison et al., 2023; Valenca et al., 2021). This study shows that replacing sand with alternative bulking agents such as ESCS would improve *E. coli* removal in both uncompacted and compacted soil, but the benefit of ESCS is particularly more prominent in uncompacted amended soil. Unlike solid sand grain, porous ESCS media has a higher surface area with more reactive sites. ESCS could also adsorb metals and other chemicals that could inactivate *E. coli* after their initial attachment (Borthakur et al., 2022a). This result is particularly important because the hydraulic retention time of stormwater in ESCS-amended soil was lower than that of sand-amended soil in the uncompacted column. Compacted sand-amended soil and biochar mixture removed more *E. coli* than compacted ESCS-amended soil-biochar mixture, possibly because of extra removal of *E. coli* by straining. The hydraulic conductivity of sand-amended soil and biochar mixture decreased drastically after compaction due to pore blockage by broken biochar particles (Le et al., 2020). Thus, extra removal came at the cost of a net reduction in the water treatment volume. It should be noted that the *E. coli* removal in our study was unusually high, possibly because the soil either adsorbed more *E. coli* or was toxic to *E. coli*. This explains why the sand and soil mixture removed more than one log *E. coli* (Fig. S4). Thus, the benefit of ESCS media might have been more apparent in soils with low *E. coli* adsorption capacity.

4.4. Cause of improved metal removal in ESCS-amended soil

In road runoff, metal concentration can be high, and sand has little capacity to adsorb dissolved metal. Our results show that an addition of ESCS to the soil mix can improve their capacity to adsorb metals. The metal removal decreased in both sand and ESCS with an increase in exposure to metal-contaminated runoff, indicating exhaustion of their adsorption capacity. However, the exhaustion rate was slower in ESCS than in sand, indicating the performance life of ESCS-amended soil would last longer than sand-amended media. The result is consistent with other studies (Kalhori et al., 2013b; Shojaeimehr et al., 2014). ESCS media could adsorb metals via adsorption and complexation due to their high cation exchange capacity (Borthakur et al., 2022a). Some clay or shale exhibits high metal removal capacity. As ESCS media is composed of expanded clay and shale, ESCS adsorbed more metals than silica sand. In our previous study (Borthakur et al., 2022a), injecting 500 PV of water contaminated with a high concentration of metals did not exhaust 10% of the capacity, indicating that the addition of ESCS can extend the performance lifetime for a decade or longer based on the pollutant loading and the amount of ESCS used in the filter media.

4.5. Conceptual understanding of why ESCS can be a better bulking agent than sand

Our results proved that ESCS could provide many benefits over sand if used as a bulking agent in amending roadside soil. ESCS can simultaneously increase the hydraulic conductivity of soil to quickly handle a large volume of runoff without diminishing water retention during a long drying period between rainfall events. ESCS enables high infiltration by virtue of their large aggregate size, which can be controlled based on design specifications. ESCS has intraparticle pores that are preserved despite compaction and retain water. In contrast, sand grains do not have any internal pores, and water retention in sand arises from interparticle pore space, which is determined by packing density and soil pore size. If the sand and soil mixture is heavily compacted, then the macro and mesopores are converted to micropores, thereby decreasing the water availability for plants. Thus, a combination of large aggregate size, their ability to withstand compaction, and preserved mesopores and micropores in intraparticle spaces enable ESCS to provide better

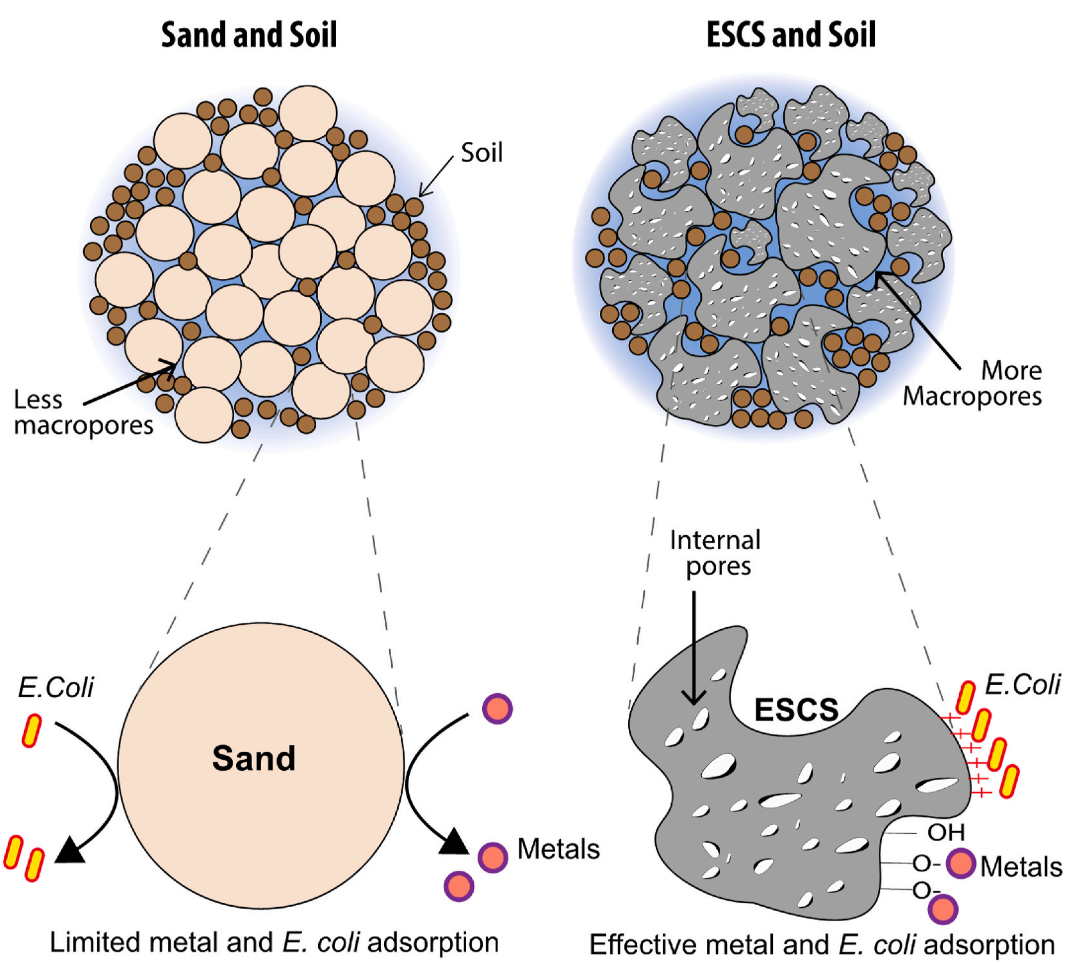

Fig. 5. Conceptual illustration showing ESCS could have many advantages over sand due to their shape, internal pores, and reactive surfaces.

hydraulic functions than sand in green infrastructure (Fig. 5). ESCS also exhibited a much higher capacity to adsorb metals and *E. coli* than sand. Sand is made out of silicate, which has limited surface areas and reactive sites to adsorb any pollutants (Tirpak et al., 2021). In contrast, ESCS aggregates are made of shale, clay, and slates, which are stabilized at high heat. This creates a reactive surface that can absorb pollutants. Previous studies provided a mechanistic explanation of why ECSC could adsorb more metals and *E. coli* (Borthakur et al., 2022a), and our study corroborated that evidence under compaction and in the presence of soil.

4.6. Environmental implications

The results have far-reaching implications for redesigning the clear zone that could serve as a climate-resilient stormwater treatment system. An increase in infiltration capacity would help infiltrate high-flowing road runoff. The use of ESCS in other locations without compaction could help the distributed stormwater treatment system to soak more water from runoff during high-intensity rainfall events, which are projected to become more frequent during climate change. Increasing the water-holding capacity of the filter layer could make the plants survive longer during long drying periods and reduce the overall maintenance cost. The amended soil in CZ serves as the initial barrier to capture first-flush samples from road runoff following rain, which contains high concentrations of pollutants. The high pollutant removal capacity of ESCS compared to sand can also lower the burden of using a separate amendment other than a bulking agent to meet the pollutant removal goal. As road runoffs are often polluted with metals, ESCS provides a better alternative to meet the TMDL requirement. Further, ESCS is derived from natural materials like shales, clays, and slates, by vitrifying them at exceptionally high temperatures. It is environmentally inert, non-toxic, and dimensionally stable and performs for long periods, which collectively makes it an ideal amendment to mitigate environmental risks from contaminated stormwater. ESCS is a lightweight material with a mean density of 1.25–1.65 g cm^{-3}, compared to the sand density of 2.65 g cm^{-3}. Thus, this would reduce the shipping cost to specific locations. Nevertheless, most of the cost associated with road design is related to construction with a small fraction contributed by material. Thus, ECSC has the potential to be used as an alternative bulking agent in the clear zone to offer sustainable stormwater treatment in different climates.

5. Conclusions

This study examined whether amending the roadside soil in the clear zone with sand or ESCS could increase infiltration despite compaction and provide other intended functions during extreme hydrological conditions such as high-intensity rainfall and drought. Compared to sand-amended soil, ESCS-amended soil doubled infiltration capacity and enhanced the water holding capacity by 58%, thereby increasing plant-available water and groundwater recharge. This could potentially increase the resilience of vegetation during long drying periods between rainfall events. ESCS also provided additional benefits of higher pollutant removal capacity than sand, particularly for *E. coli* and heavy metals. The total metal content removal increased by 21% in the ESCS-amended media filter. The results indicate that ESCS media possess a unique characteristic as a bulking agent that, despite having a larger aggregate size, they increase both infiltration capacity and water retention. Replacing sand with ESCS in stormwater control measures could improve their ability to withstand extreme hydrological conditions such as high-intensity rainfall by quickly infiltrating water and long drying periods by retaining more water near the root zones. Thus, including ESCS as soil amendment in the clear zone could turn part of the transportation infrastructures from a source of pollution into a network of sustainable water solutions in water-stressed space-constrained urban areas.

CRediT authorship contribution statement

Tonoy K. Das: Conceptualization, Methodology, Data curation, Formal analysis, Sampling, Visualization, Writing – original draft. **Onja D. Raoelison:** Data curation, Writing. **Hamid Rehman:** Data curation, Methodology. **Yuhui Zhang:** Data curation, Methodology, Sampling. **Wendy Chau:** Data curation, Methodology, Sampling. **Lisa Thamiz:** Data curation, Methodology, Sampling. **Michael K. Stenstrom:** Writing – review & editing. **Sanjay K. Mohanty:** Conceptualization, Visualization, 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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.139443.

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