

Hydraulic and Water Quality Performance of Bioretention Filter Media: Insights from Controlled Column Experiments

Performance hydraulique et de traitement de l'eau de médias filtrants de biorétention : Enseignements tirés d'expériences en colonnes contrôlées

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RÉSUMÉ

L'urbanisation rapide a accru les surfaces imperméables, perturbant les processus hydrologiques naturels et augmentant les volumes et débits de pointe du ruissellement, ainsi que le risque d'inondation en lien avec le changement climatique. Les systèmes de biorétention, une stratégie clé de gestion à faible impact (LID), atténuent ces impacts en rétablissant certaines fonctions hydrologiques, mais leur performance dépend fortement des médias filtrants utilisés qui doivent présenter un compromis entre capacité de filtration et efficacité hydraulique. Cette étude évalue trois technosols mixtes composés d'une base de sable-sol (50:50) amendée avec des proportions croissantes de balle de riz carbonisée (CRH), à l'aide d'expériences en colonnes contrôlées mesurant la performance hydraulique (réduction du débit de pointe et du volume) et l'élimination des matières en suspension (MES). Les résultats préliminaires montrent que le média non amendé présente la performance la plus équilibrée, atteignant plus de 90 % d'atténuation des débits de pointe, jusqu'à 47 minutes de temps de latence et environ 2 heures de temps de détention hydraulique, favorisant ainsi l'élimination des MES. Les expérimentations en cours permettront de clarifier le rôle de la CRH sur la performance des médias filtrants.

ABSTRACT

Rapid urbanization has increased impervious surface cover, disrupting natural hydrologic processes and intensifying stormwater runoff volumes and peak flow rates, with climate change further heightening urban flood risk. Bioretention systems, a key low impact development (LID) strategy, help mitigate these impacts by restoring hydrologic functions, yet their performance depends on engineered soil media that must balance filtration capacity with hydraulic efficiency. This study evaluates three advanced engineered soil mixes composed of a 50:50 sand-soil base amended with increasing proportions of carbonized rice husk (CRH) through controlled column experiments assessing hydraulic performance (peak flow attenuation and volume reduction) and water quality performance based on total suspended solids (TSS) removal. Preliminary results indicate that the unamended control media provided the most consistent and balanced hydraulic detention performance, achieving greater than 90% peak flow attenuation, up to 47 minutes of lag time, and ~2 hours of hydraulic detention time, which enhances TSS removal. However, simulation experiments are currently underway to evaluate runoff retention behavior and further validate the retention performance of the filter media, particularly under varying flow conditions and pollutant concentrations. These ongoing investigations will help clarify the role of CRH amendments in enhancing or diminishing overall bioretention functionality.

KEYWORDS

bioretention, carbonized rice husk, advanced engineered soil media, hydraulic detention, water quality

1 INTRODUCTION

Climate change and the rapid expansion of impervious surfaces in urban areas have disrupted natural hydrologic cycles, increasing stormwater runoff volumes, peak flows, and pollutant loads to receiving waters (Choi et al., 2018). Bioretention systems have become a key Low Impact Development (LID) strategy for mitigating these impacts by enhancing infiltration, providing hydraulic detention and retention, and removing pollutants through filtration and biological processes (Hong et al., 2017). However, conventional bioretention media often face limitations in balancing hydraulic performance and pollutant removal. High permeability promotes rapid drainage, yet longer residence times are generally needed to enhance filtration efficiency (Hsieh & Davis, 2005). Laboratory evaluations often rely on constant-head testing, which fails to represent the unsteady hydraulic conditions of real storm events that can alter contact time, sediment settling, and resuspend previously captured solids (Li & Davis, 2008). To address these challenges, this study evaluates advanced engineered soil media (AESM) designed to improve hydraulic detention and retention, and sediment removal under dynamic flow conditions. The results presented here reflect initial findings from the hydraulic detention experiments; additional data from ongoing hydraulic retention simulations will be incorporated into the full paper as these analyses are completed.

2 MATERIALS AND METHODS

Three laboratory-scale bioretention columns were set up (Figure 1) to evaluate both hydraulic detention and retention behavior, as well as TSS removal, under controlled conditions. Each column measured 1000 mm in height and 93 mm in diameter and consisted of a ponding zone, mulch layer, engineered soil layer, transition layer, and drainage layer. The engineered soil layer was varied by incorporating carbonized rice husk (CRH) at 0% (control), 10%, and 20% by weight into a standard 50:50 sand–soil mix, while coconut fiber, sand, and gravel served as the mulch, transition, and drainage layers, respectively. Synthetic stormwater runoff was created by diluting road-deposited sediments with tap water to produce three TSS concentrations reflecting field conditions: low (190–300 mg/L), medium (860–1200 mg/L), and high (1320–2500 mg/L), based on ranges reported by Sanchez et al. (2011).

Each column underwent several trials with increasing influent concentrations. For the detention experiments, the outlet valve was positioned at the bottom to allow full drainage and measurement of hydraulic response; for retention experiments (currently ongoing), the valve was placed at the top to increase water–media contact and promote runoff storage. During each detention trial, influent samples were collected every minute, while effluent water was sampled at staggered intervals (every 15 seconds initially, then at 2-minute, 5-minute, 30-minute, and hourly intervals) until flow became negligible.

Flow rates were calculated as volume over sampling time and integrated over the full outflow duration to determine total effluent volume. TSS concentrations of flow-weighted composite effluent samples were analyzed using ASTM D5907-13. Hydraulic parameters—including peak flow attenuation, lag time, hydraulic detention time, and retention behavior—were quantified to assess overall bioretention media performance.

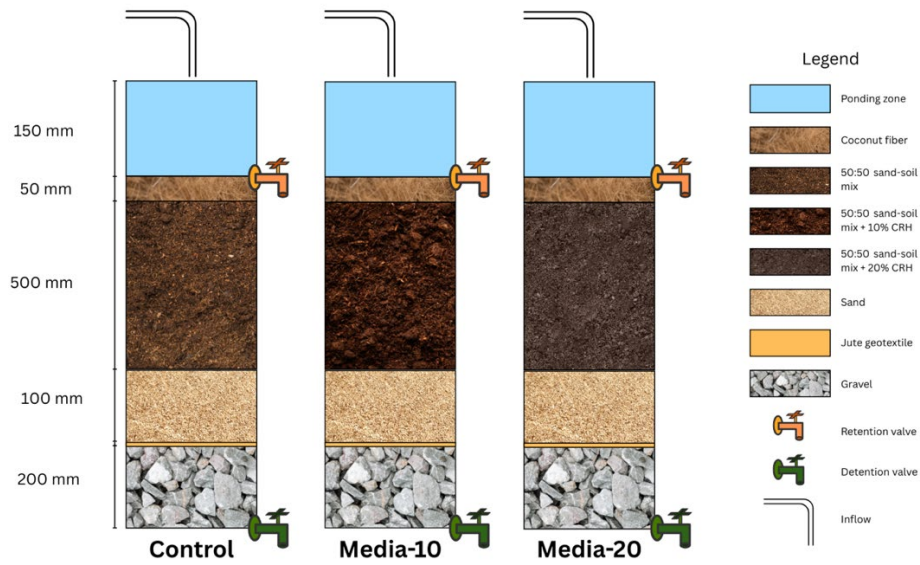


Figure 1. Schematic diagram of three filter media columns

3 RESULTS AND DISCUSSION

3.1 Peak flow

As shown in Figure 2, peak flow reduction was greatest under low influent concentrations and declined as concentration increased across all filter media. At low TSS levels, fewer suspended particles entered the system, allowing both micropores and smaller interconnected pores to function effectively in slowing internal flow, resulting in stronger attenuation. The control media, with its higher proportion of micropores, consistently exhibited the strongest reduction, while Media-10 showed intermediate performance and Media-20 the lowest.

At higher concentrations, peak flow attenuation decreased due to the combined effects of early surface clogging and increased preferential flow. As more solids accumulated at the surface and within finer pores, inflow was redirected toward larger macropores—particularly prevalent in the CRH-amended mixes.

These macropores provided quicker drainage routes, reducing flow resistance and shortening the time to reach peak outflow. This mechanism explains both the reduced attenuation at high TSS concentrations and the consistently lower performance of Media-20, which contained the largest proportion of macropores. Overall, the results highlight that peak flow behavior is strongly affected by both pore size distribution and influent sediment load.

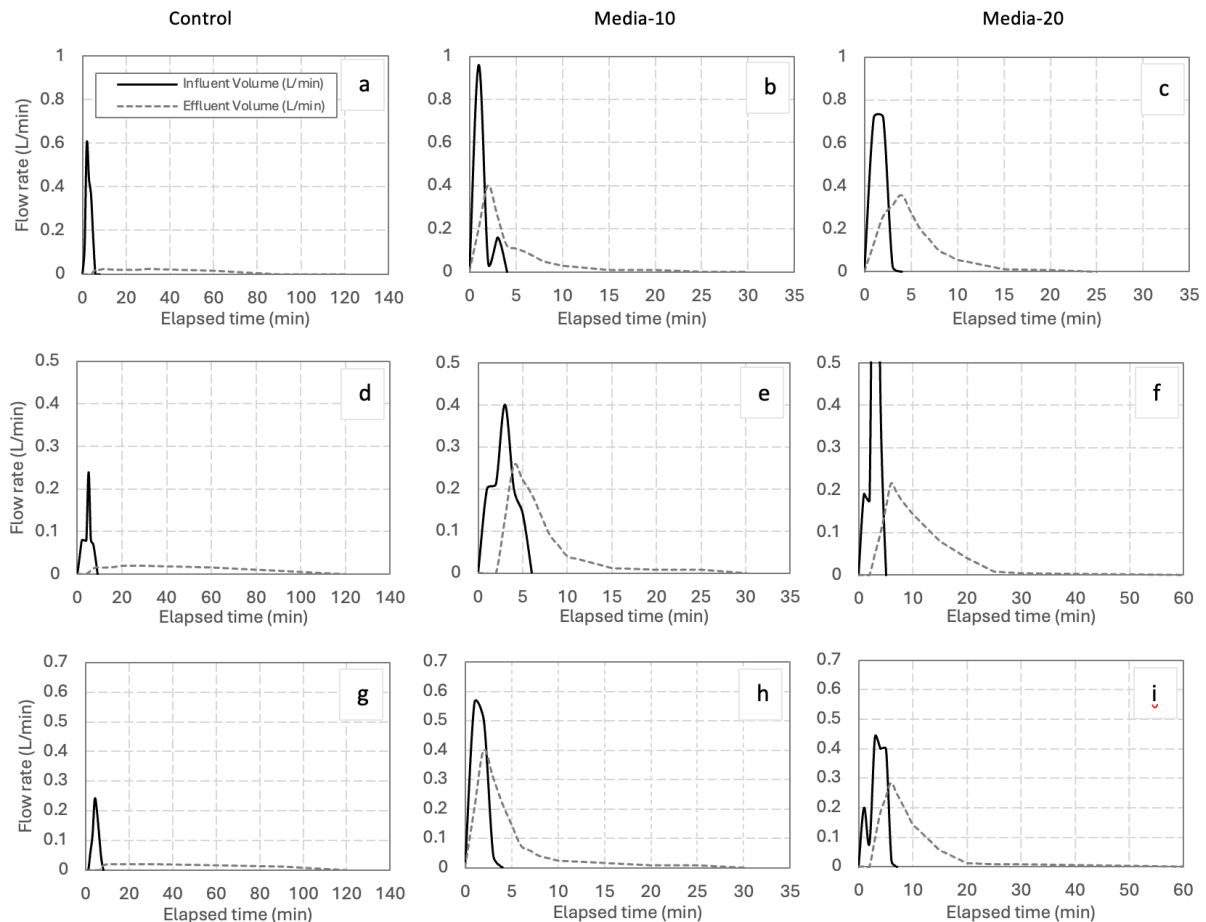


Figure 2. Representative influent and effluent hydrographs for the Control, Media-10, and Media-20 columns under low (a–c), medium (d–f), and high (g–i) influent TSS concentrations.

3.2 Lag time

Lag time showed distinct differences among media types and decreased with increasing influent concentration (Figure 2). At low concentration, the control column exhibited the longest delay (36 min), while Media-10 (3.3 min) and Media-20 (4.0 min) showed much shorter responses. At medium concentration, lag times followed a similar pattern, with the control at 44 min, compared with 4.5 min for Media-10 and 8.7 min for Media-20. At high concentration, the control again produced the longest delay (47 min), whereas Media-10 (3.6 min) and Media-20 (7.2 min) drained more quickly.

The consistently longer lag times in the control media reflect its higher proportion of micropores, which slow internal water movement and extend the time required for discharge. In contrast, CRH-amended mixes contain more macropores, enabling faster flow and therefore shorter lag times. The reduction in lag time at higher TSS concentrations suggests that partial surface clogging may redirect inflow toward larger macropores, especially in CRH-amended media, further accelerating outflow.

3.3 TSS Removal Efficiency vs. Hydraulic Detention Time (HDT)

A positive linear relationship was observed between TSS removal efficiency and hydraulic detention time (HDT), with Media-20 providing the only consistent dataset for generating an empirical trend. Because the outlet valve was positioned at the bottom to emphasize detention, Media-20 exhibited a sufficient range of HDT values to show increasing removal with longer residence time. The resulting equation, $\text{TSS Removal (\%)} = 0.9116 \times \text{HDT} + 30.998$ ($R^2 = 0.7992$), indicates that each additional minute of detention increased TSS removal by nearly 1%. For

the control and Media-10 columns, the limited HDT variability prevented the development of a reliable trend, suggesting that additional tests are needed to establish a conclusive relationship for those media.

Figure 3. Relationship between TSS removal efficiency and hydraulic detention time (HDT) for the Media-20 column

4 CONCLUSION

This study presents the initial findings from laboratory experiments focused on hydraulic detention, using a bottom-valve configuration that directed flow through the entire media profile. Under this setup, the control media consistently showed the highest peak flow attenuation and longest lag times, reflecting its greater proportion of micropores and higher internal flow resistance. In contrast, CRH-amended media exhibited faster flow and lower attenuation due to increased macroporosity. Peak flow and lag time both decreased with higher influent concentrations, indicating the combined influence of sediment loading, early surface clogging, and the activation of preferential macropore pathways. Hydraulic detention time strongly influenced TSS removal, with Media-20 producing the only clear empirical trend between detention and removal efficiency. Additional trials are needed to generate comparable relationships for the control and Media-10 columns, where detention time variability was more limited. Because these results represent detention-only behavior, a more complete assessment of media performance will include the ongoing retention experiments, which use a top-valve configuration to increase water-media contact and encourage runoff storage. These forthcoming data will complement the detention findings and help determine the suitability of CRH-amended engineered soils for optimizing bioretention systems in tropical environments.

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