Urban stormwater nutrient and metal removal in small-scale green infrastructure: exploring engineered plant biofilter media optimisation

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ABSTRACT

The present study evaluated engineered media for plant biofilter optimisation in an unvegetated column experiment to assess the performance of loamy sand, perlite, vermiculite, zeolite and attapulgite media under stormwater conditions enriched with varying nutrients and metals reflecting urban pollutant loads. Sixty columns, 30 unvegetated and 30 Juncus effusus vegetated, were used to test: pollutant removal, infiltration rate, particulate discharge, effluent clarity and plant functional response, over six sampling rounds. All engineered media outperformed conventional loamy sand across criteria, with engineered attapulgite consistently among the best performers. No reportable difference existed in vegetation exposed to different material combinations. For all media, the results show a net removal of NH₃-N, PO₄³⁻-P, Cd, Cu, Pb and Zn and an increase of NO₃⁻-N, emphasizing the importance of vegetation in biofilters. Growth media supporting increased rate of infiltration whilst maintaining effective remediation performance offers the potential for reducing the area required by biofilters, currently recommended at 2% of its catchment area, encouraging the use of small-scale green infrastructure in the urban area. Further research is required to assess the carrying capacity of engineered media in laboratory and field settings, particularly during seasonal change, gauging the substrate’s potential moisture availability for root uptake.

Key words: biofiltration, ecological engineering, engineered media, green infrastructure, stormwater

HIGHLIGHTS

- This is the first study to investigate the novel addition of attapulgite media for urban pollutant removal from stormwater in biofilters.
- The experiment reported consistent and effective removal of ammonia, orthophosphate an heavy metals.
- The paper reports a time-lapse of photographic evidence illustrating the change in sediment discharge from new biofilters.
- Infiltration rate enhanced, while pollutant removal performance was maintained.
INTRODUCTION

Pollution associated with increasing urbanisation impacts both human and environmental health (McGrane 2016). Stormwater runoff from impermeable and semi-permeable areas in urban centres such as parking lots, sidewalks and rooftops have resulted in larger peak flows, flow volumes and pollutant loads that are typically discharged into urban surface waters (Fletcher et al. 2015). This increases the ecotoxicity risk on surface- and groundwater (Gosset et al. 2017), thereby threatening entire aquatic ecosystems, posing a drainage challenge to urban water engineers (Brudler et al. 2019).

Plant biofiltration, a green infrastructure (GI) technology, is an ecologically acceptable method for urban stormwater management and have shown promising results for the on-site reduction of peak flows, removal of environmental contaminants and protection of urban waters (Armitage et al. 2014). From a technical perspective, plant biofilters can be easily introduced into the urban landscape, with small-scale biofilters best applied in dense built-up areas and large-scale biofilters most effective at distinct stormwater network confluences (Le Coustumer et al. 2012).

It has, however, been found that a distinct disadvantage of plant biofilter performance is that it can deteriorate over time, leading to more frequent overflows, extended ponding time, increased particulate discharge and reduced pollutant treatment particularly for heavy metals and nitrate (Le Coustumer et al. 2009; Al-Ameri et al. 2018). Incorrect media selection is a common cause of poorly functioning or failed systems, resulting in leaching, channel clogging and plant mortality (Payne et al. 2015). Furthermore, inadequately functioning growth media negates intricate planning and design, which considers plant and media selection as essential contributors to performance and sustainability (Le Coustumer et al. 2012). Media selection has therefore been indicated to be a very important design element in plant biofiltration technologies.

In an effort to optimise plant biofilters, the introduction of engineered growth media such as zeolite (see Li et al. 2014), perlite (see Le Coustumer et al. 2012) and vermiculite (see Li et al. 2018) in combination with traditional loamy sand as a carbon source (see Bratieres et al. 2008) may potentially increase stormwater remediation efficacy and biofilter longevity (Chandrasena et al. 2017). It is therefore important to not only optimise growth media, but also to consider the effects of the media on plant health and vitality (Malézieux et al. 2007).
Loamy sand, typically used as growth media, with a low nutrient content, is effective for the remediation of certain stormwater pollutants (Milandri et al. 2012). Although it provides adequate support for plant growth, it frequently is lacking in preventing pathogen, heavy metal and nutrient (particularly nitrate) leachate (Hsieh & Davis 2003). Perlite and vermiculite are capable of adsorbing both organic and inorganic substances and are often used in stormwater management systems as filtration and anti-clogging media (Hashem et al. 2015). For the removal of heavy metals, vermiculite is better equipped due to its cation exchange capacity (Hatt et al. 2007). In removing nutrients, the use of perlite or vermiculite in isolation is inadequate due to the prevalence of nutrient leachate (Prodanovic et al. 2018). Zeolites are environmentally and economically acceptable hydrated materials with effective ion-exchange, sorption and acid catalysis properties and are well known to remove organic and inorganic pollutants (Chmielewska 2015). For some pollutants however it has been inconsistent, with pathogen and heavy metal removal inefficiencies reported (Mamba et al. 2009). Attapulgite, with its high adsorption capacity, porous structure, high surface area and cation exchange capacity offers potential as growth media to biofilters (Zhang et al. 2015). It is inexpensive and has been reported to show great potential in practical environmental remediation (Tichapondwa & Van Biljon 2019). Although overlooked for implementation in biofilters, this material offers a possible alternative to conventional ineffective media, specifically for the remediation of nutrient and heavy metal pollutants.

A need for research relating to a clear delineation of relative media proportions to use, as well as how different combinations would affect remediation performance, plant stress, infiltration capacity, particulate transport and longevity has been suggested in literature (see Prodanovic et al. 2018). Additionally, research on the evaluation of nanocomposite attapulgite for use in biofilters is warranted (Wang et al. 2018). Although considerable efforts have been made to assess the role of vegetation in maintaining long term biofilter performance, research into growth media has generally been limited, with typical investigations focusing predominantly on single use media (Chandrasena et al. 2017). Further research into media combinations towards plant biofilter media improvement is therefore required.

This paper presents the results of an exploratory laboratory study on the optimisation of plant biofilter growth media for urban stormwater biofiltration. An experimental approach was used to establish the performance of unvegetated loamy sand, perlite, vermiculite, zeolite and attapulgite media combinations. In an effort to assess plant biofilter success, a secondary investigation evaluated media infiltration and solids discharge in the presence and absence of vegetation. Additionally, plant functional response to media and typically observed urban pollutants were evaluated by assessing the above- and below-ground traits of Juncus effusus, irrigated with synthetic stormwater and potable municipal water.

**METHODOLOGY**

**Biofilter design**

In order to explore media optimisation, 60 biofilter columns were constructed from Ø110 mm × 600 mm PVC piping, complying with stormwater design guidelines as recommended by Payne et al. (2015). Each column included a drainage zone covering the drainage outlet below the transition layer, topped with 450 mm growth filter media of varying combinations to support plant establishment (see Figure 1).

The inner walls of the columns were abraded to minimise preferential flow and sealed at the base, allowing effluent extraction for analyses. Growth media included material at varying ratios, maintaining infiltration rates of 100–300 mm/hr at the start of the study, with 30 unvegetated columns assessing the filtration performance of growth media only. Additionally, 30 vegetated columns containing Juncus effusus were used to assess plant response to urban pollution, plant stress in varying media, and effect on infiltration and sedimentation. The growth media consisted of varying combinations of loamy sand, perlite, vermiculite, zeolite and attapulgite with particle size distributions with ranges as shown in Table 1 below.

The Juncus effusus plants were approximately 24 months old and sourced from a local nursery prior to transplantation into the experimental columns. Special care was taken to remove all foreign organic matter and soil from the roots. During transplantation a half-strength Hoagland solution was added to all vegetated columns to provide essential nutrients to support growth (see Li & Cheng 2015). Both the vegetated and unvegetated biofilter columns were subjected to twice-weekly watering using municipal tap water for 18 weeks to provide time for plant establishment and natural hydraulic compaction (Read et al. 2008). This period was followed by 10 weeks of synthetic dosing to reflect local urban stormwater pollution and runoff events for all the unvegetated columns and half of the vegetated columns. The remaining vegetated columns received municipal tap water, to assess plant functional response to engineered media in the absence of nutrient and metal pollutants.
Experimental design

A preliminary investigation of the saturation rate of the media at varying influent volumes was done using clear perspex columns, which allowed visible tracing of the drop in water level. This was used to establish media ratios that were practically capable of maintaining the recommended 100–300 mm/hr rate (Payne et al. 2015). Previous biofilter studies investigating pollutant removal of engineered media (excluding loamy sand), showed performance to be in the order zeolite > vermiculite > perlite, with attapulgite, effective in pollutant removal from aqueous solutions, overlooked for use in biofilters (Al-Sharify & Athab 2012; Zinger et al. 2013; Chandrasena et al. 2017; Prodanovic et al. 2018; Tichapondwa & Van Biljon 2019).

Therefore, some effort was made to implement greater proportions of the most effective material, see Table 2 below. A low initial unvegetated infiltration rate was selected due to vegetation’s ability to increase infiltration and decrease clogging (Le Coustumer et al. 2012). Ten different media of varying material contributions, supporting rhizospheric conditions and pollutant interaction, whilst encouraging plant growth were evaluated. Three replicates of each growth media was used.

For practicality during biofilter construction, the filter material was added as a mixture above the transition layer, as opposed to a layered design. Columns LSPVZ and LSPVA exchanged the normal coarse sand transition layer for coarse zeolite (ZE3) and attapulgite (AT2) respectively, with both offering additional remediation as opposed to filtering fine particles only.

Table 1 | Particle size distribution of the material

| Material       | Size (mm) | Identifier |
|----------------|-----------|------------|
| Loamy sand     | 0.05–3.4  | LS         |
| Perlite        | 1–3       | PE         |
| Attapulgite    | 0.5–1.4   | AT1        |
| Attapulgite    | 1.4–4.5   | AT2        |
| Vermiculite    | 0.35–0.5  | VE1        |
| Vermiculite    | 0.5–1.4   | VE2        |
| Vermiculite    | 1.4–2     | VE3        |
| Vermiculite    | 2–6       | VE4        |
| Vermiculite    | 0.8–1.4   | ZE1        |
| Zeolite        | 1.4–2     | ZE2        |
| Zeolite        | 2–4       | ZE3        |

Figure 1 | Schematic of experimental biofilter, vegetated Juncus effusus and unvegetated columns.
Stormwater dosing and monitoring

Synthetic stormwater was prepared from analytical grade compounds to correspond with local Stellenbosch (South Africa) urban pollutant levels (Rauch & Brink in preparation), as well as global urban water pollutant concentrations as depicted in Table 3 (Göbel et al. 2007; Bratieres et al. 2008; Barron et al. 2019). Synthetic stormwater was continuously mixed in a storage tank to ensure uniform dispersion and irrigated with an automated drip irrigation system, with influent concentrations monitored throughout.

Equation (1) calculated dosage volumes ($V_i$) to simulate appropriate biofilter influent volumes under impermeable area surface dynamics based on the characteristics of the Stellenbosch urban area (South Africa). The effect of specific watershed

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**Table 2 | Engineered filter media proportions for initial infiltration within 100–300 mm/hr range**

| Identifier | Representative media | Contribution (volume) | Infiltration rate (mm/hr) |
|------------|-----------------------|-----------------------|--------------------------|
| LS         | LS                    | 1                     | 112                      |
| LSP        | LS:PE                | 3:2                   | 125                      |
| LSV        | LS:VE1:VE2           | 3:1:1                 | 121                      |
| LSZ        | LS:ZE1:ZE2           | 3:1:1                 | 147                      |
| LSA        | LS:AT1               | 3:2                   | 162                      |
| LSPV       | LS:PE:VE1:VE2       | 6:0.5:1.75:1.75      | 170                      |
| LSPZ       | LS:PE:ZE1:ZE2       | 6:0.5:1.75:1.75      | 179                      |
| LSPA       | LS:PE:AT1           | 6:0.5:3.5             | 202                      |
| *LSPVZ*    | LS:PE:VE1:VE2:ZE1:ZE2| 5:0:0.25:0.25:1.75:1.75 | 212                      |
| *LSPVA*    | LS:PE:VE1:VE2:AT1   | 5:0:0.25:0.25:3.5    | 218                      |

*Transition layer's coarse sand media exchanged for *ZE3 (2–6 mm zeolite) and *AT2 (1.4–4.5 mm attapulgite).

**Table 3 | Influent pollutant concentrations**

| Pollutant | Parameter   | Concentration $C_i$ (mg/L) | Source     |
|-----------|-------------|-----------------------------|------------|
| Nutrients | Ammonia-N  | 0.40                        | NH$_4$Cl    |
|           | Nitrate-N  | 0.95                        | KNO$_3$    |
|           | Orthophosphate-P | 0.35          | K$_2$HPO$_4$ |
| Metals    | Cd          | 0.0045                      | CdCl$_2$   |
|           | Cu          | 0.045                       | CuSO$_4$   |
|           | Pb          | 0.15                        | PbCl$_2$   |
|           | Zn          | 0.30                        | ZnCl$_2$   |
conditions on influent concentrations was omitted, thus we considered the rate at which stormwater accumulate pollutants to be uniform across influent. It was attempted to include contributing runoff factors despite the fact that the outcome of this equation may not have been an entirely accurate depiction of runoff. This study was, however, designed to be performed under laboratory conditions in which influent variability was limited rather than, necessarily, to precisely model and scale runoff volumes. Further explanation of reasoning behind included factors is discussed below. This produced a twice-weekly drip dosing per filter setup of 0.63 L, as well as an increased dosing of 9.41 L at 60-day intervals which lasted several hours to simulate average annual rainfall- and intense uninterrupted storm-event volumes respectively, for Ø110 mm biofilter columns in the local urban catchment:

\[ V_i = \left( \frac{A_b}{K_a} \times P \right) \times K_r \]  

(1)

where

- \( V_i \): influent dosage volume (L)
- \( A_b \): area of biofilter (m²)
- \( K_a \): biofilter percentage of contributing catchment area (%)
- \( P \): precipitation event rainfall (mm)
- \( K_r \): percentage urban runoff (%)

In urban areas impermeable surfaces increase runoff volume and elevate peak discharge into stormwater biofilters, however, not all rainfall is translated to runoff, with permeable and impermeable infiltration and evapotranspiration reducing runoff flow (Ragab et al. 2003; Rammal & Berthier 2020). Hence dosage volumes, influenced by the contributing catchment area's extent and type of imperviousness must account for potential runoff losses over site-specific urban surfaces. Fortunately, the integrative nature of imperviousness allows for predicting cumulative water resource impacts, which include the contribution of hydrological changes to runoff volume and non-point source pollution, but only if the extent of the contributing catchment area is defined (Schueler 1992).

For Stellenbosch, Musakwa & Van Niekerk (2015) reported a 19% increase in impermeable surface area from 777.6 to 925.2 ha in the decade from 2000 to 2010. Following this trend, we interpolated imperviousness for 2020 to be 1,072.9 ha of the total 2,475 ha area, amounting to 43.4% of Stellenbosch's area. This level of imperviousness, between 35 and 50%, corresponds with a 30% conversion of precipitation to urban runoff, with the remaining 35, 20 and 15% lost to evapotranspiration, shallow infiltration and deep infiltration respectively (Arnold & Gibbons 1996). In estimating the volume required to reflect typical biofilter inflow, an assessment of typical and uninterrupted intense Stellenbosch storm events produced an average annual rainfall of 619 mm of which three 66 mm intense rainfall events occur, based on the local climatic pattern from 2010 to 2020 (SAWS 2020). To avoid overwhelming the biofilter, shortening its lifespan and hindered remediation efficacy, an appropriate minimum biofilter size of at least 2% of the catchment area contributing runoff to the biofilter’s inflow volume is required (Payne et al. 2015). Due to the laboratory design of the experiment using Ø110 mm biofilter columns, the corresponding contributing runoff area was adjusted, altering the runoff volume available for discharge into the system. Therefore, in summary, the dosage volumes were calculated based on 50% urban runoff conversion at 43.4% imperviousness for Stellenbosch, sized at 2% of its potential contributing catchment area, receiving twice-weekly dosages of 2.08 and 66 mm every 60 days to reflect typical- and maximum intense- precipitation events respectively.

**Pollutant removal**

The pollutant removal efficiencies of the media combinations were evaluated with effluent sampling initiated 30 days after the first day of synthetic stormwater dosing at 10-day intervals, collected in 500 mL containers directly below the drainage pipes of each unvegetated biofilter column. This 30-day period allowed for the transport of excess non-polluted tap water that may have lingered within the growth media, thus, negating pollutant dilution. Thirty days were proven sufficient by evaluating the transport time required for a water soluble dye to be discharged from the experimental biofilter columns. Vegetated *Juncus effusus* columns were excluded for pollutant removal analysis. Samples were collected on six occasions, with the first sample round evaluating the existing concentration prior to dosing.

Pollutant load removal efficiencies cannot be quantified by analysing concentration alone, as biofilters are not closed systems, with volume loss occurring due to plant-water uptake and evapotranspiration. Thus, pollutant load removal must
account for the difference in concentration, as well as the alternating influent volumes and measured effluent volumes. Overall pollutant removal percentage efficiencies for each biofilter was calculated as the mean across all sampling rounds ($\bar{K}_{\text{rem}}$), Equation (2):

\[
K_{\text{rem}} = \frac{C_i V_i - C_e V_e}{C_i V_i} \times 100
\]

where

- $K_{\text{rem}}$ = pollutant load removal (%)
- $C_i$ = influent concentration (mg/L)
- $V_i$ = influent dosage volume (L)
- $C_e$ = effluent concentration (mg/L)
- $V_e$ = effluent volume (L)

Various water quality parameters were analysed in the Stellenbosch University Water Quality Laboratory to determine the performance of each of the ten media combinations. These included pH, dissolved oxygen (DO), electrical conductivity (EC), ammonia-N (NH$_3$-N), nitrate-N (NO$_3$-N) and orthophosphate-P (PO$_4$$_3$-P). Cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn) were analysed at the Stellenbosch University Central Analytical Facility: ICP-MS division.

The pH, DO and EC were measured using a HACH HQ440d Benchtop Multi-Parameter. Measurement of nutrient and metal concentrations required effluent filtration with a 0.45 μm syringe filter prior to analyses. The NH$_3$-N, NO$_3$-N and PO$_4$$_3$-P concentrations were measured colorimetrically using a HACH DR3900 Benchtop Spectrophotometer. The Cd, Cu, Pb and Zn concentrations were analysed on an Agilent 8,800 QQQ ICP-MS instrument, with polyatomic interferences removed by a 4th generation Octopole Reaction System.

**Infiltration capacity**

In order to assess media infiltration capacity under typical and intense storm events, the twice-weekly and 60-day interval dosages were administered. This was done by comparing the infiltration rate (IR) between the various unvegetated columns, as well as with their vegetated counterparts over time. The surface infiltration rate measurements were taken at 20-day intervals, with the first round of sampling initiated on the day the growth medium was added and the vegetation planted, after which the columns received dosing. This sampling regime produced 11 measurements over a 28-week period throughout the experiment, adequate time to achieve hydraulic compaction (Le Coustumer et al. 2012). The Falling Head test applied immediately following dosing of the columns on the day of sampling, measured the drop in depth of the ponded influent relative to the medium surface at 1 minute intervals, Equation (3). The average hydraulic performance for each column was calculated as the slope of the drop in water level across the measurement time (mm/hr) (Knappett & Craig 2012):

\[
k = 2.3 \frac{aL}{A (t_1 - t_0)} \log \frac{h_0}{h_1}
\]

where

- $k$ = coefficient of permeability (m/s)
- $a$ = cross-sectional area of the column (m$^2$)
- $L$ = growth media depth (m)
- $A$ = cross-sectional area of growth media (m$^2$)
- $t_1 - t_0$ = elapsed time between head readings (s)
- $h_1 - h_0$ = head readings taken at $t_1$ and $t_0$ respectively (m)

As mentioned, a preliminary clear perspex column investigation of media infiltration satisfied suppressed rapidity of the head drop, substantiating the use of the above equation.

**Particulate discharge**

The role of vegetation in mitigating soil erosion and sediment discharge in urban areas during GI construction and establishment was assessed by analysing effluent deposition of the unvegetated and vegetated biofiltration columns throughout the
28-week irrigation regime. Similar to analysing infiltration capacity above, effluent sampling was initiated on the day of column establishment, taken at 20-day intervals producing 11 measurements. Comparisons were conducted between unvegetated and vegetated columns, and among media combinations. Effluent samples were analysed in triplicate for turbidity, total suspended solids (TSS) and total dissolved solids (TDS) presented as total solids (TS = TSS + TDS), in both the presence and absence of vegetation. Turbidity readings were measured using a 2100Q Portable Turbidimeter, with TSS and TDS analysed by means of the HACH DR3900 Benchtop Spectrophotometer Photometric method and the IntelliCAL CDC401 probe of the HACH HQ440d Benchtop Multi-Parameter meter, respectively.

Plant functional response

The effect of the engineered media on plant growth was evaluated by assessing above- and below-ground plant functional traits within the vegetated columns. With the conclusion of the 28-week experimental period, two whole *Juncus effusus* specimens (one receiving synthetic- and the other municipal dosing) were excavated from their biofilter columns for each of the ten media combinations and above-ground and below-ground traits measured after extraneous soil particulate and organic matter was removed. Below-ground traits were divided into number of roots and length of the longest root, which was taken to indicate the specimen’s response to media exposure. In determining plant response, root:shoot ratios were assessed. Investigating the influence of polluted urban runoff on plant growth over the extent of the experimental period, initial roots and shoots and final roots and shoots were compared between plants receiving synthetic stormwater and municipal supply.

Data analysis

To test for normality and homoscedasticity the Lilliefors test and the Bartlett test were used respectively. The one-factor ANOVA was used to ascertain the significance of difference in normally distributed results of growth media. With statistically significant difference in results found from the one-factor ANOVA, an unadjusted α pairwise t-test was performed with a pooled standard deviation to compare unvegetated and vegetated columns. Where data were not found to be normally distributed, the nonparametric ANOVA Kruskal-Wallis H-test was used to analyse differences in the growth media results, whilst the Wilcoxon Rank-Sum test was used to compare the unvegetated and vegetated columns. The Fisher Least Significant Difference (LSD) test was used to display media that are not significantly different. In this experiment statistical analyses were conducted using R Statistical Software with an unadjusted α = p-value, to maintain the power of the test (Feise 2002). Significance was accepted at p-value ≤ 0.05 = α, for all analyses.

RESULTS AND DISCUSSION

Urban pollutant remediation

In evaluating nutrient removal, all media successfully removed ammonia-N and orthophosphate-P at varying efficiencies (Table 4). For nitrate, however, a net effluent increase rather than a net decrease was found across the unvegetated media, similar to previous findings reporting nitrate-N leachate in biofilters (Bratieres et al. 2008). From Figure 2, all engineered media combinations outperformed traditional LS, reporting decrease and increase differences of 27.3%, 20.8% and 113.8% for NH3-N, PO4−3-P and NO3−-N, respectively. For the worst nutrient remediating media, traditional LS averaged percentage load removals were 49.2% and 34.9% for NH3-N and PO4−3-P respectively, as well as producing 277.3% of NO3−-N. In contrast, the best performing media was engineered LSPVA, with removal averaging 89.7% and 66.3% for NH3-N and PO4−3-P. In addition, LSPVA most effectively restricted nitrate release into the effluent, reporting a net increase of 90.3% for NO3−-N, the least by any media.

Analysis of nutrient removal by unvegetated media for NH3-N, NO3−-N and PO4−3-P did not satisfy normality, thus the non-parametric ANOVA Kruskal-Wallis H-test evaluated statistically significant differences for pollutant load removals for each nutrient. Between media, significant differences were found for NH3-N only (p = 0.0025) with no significant differences reported for NO3−-N (p = 0.075) and PO4−3-P (p = 0.23). Although differences between unvegetated media for NO3−-N and PO4−3-P removal were not significantly different, the Wilcoxon Rank-Sum test implemented a pairwise comparison, with differences represented by Fisher’s LSD test, illustrated in Figure 2.

From the results, effective ammonia reduction and nitrate increase in all media combinations suggest volatilisation at the surface area or an enhancement of the nitrification process in biofilters, converting ammonium to nitrate even in the absence of vegetation (also see Barth et al. 2020). This may be due to a weak dependence by microbial activity responsible for nitrification on plant presence (Gerardi 2003). Experiencing similar nitrate increase, Davis et al. (2001) suggested that nitrate leachate could
be the biological transformation of captured ammonia and organic nitrogen to oxidized nitrogen (nitrate and nitrite) between outflow events. In the unvegetated biofilters, due to oxidized nitrogen’s anionic form there is little adsorption onto soil, resulting in negligible removal and only minimal denitrification (Henderson et al. 2007). Under intense dosing, limiting adsorption opportunities, and inadequate denitrification to complete the nitrogen removal process, nitrate leaching increased. This observation was similar for orthophosphate-P, where minimal removal directly after an increase in dosage volume was observed. Dissolved phosphorous after these events may over time decrease, as phosphorous adsorbs to soil (Asomaning 2020).

Metal removal was effective in all media combinations with traditional LS again maintaining the lowest percentage reduction. Cd outflow concentrations were below the 0.000045 mg/L laboratory detection limit in 96% of the samples, registering only one measurable data point in two separate sampling rounds, 97.8% and 98.1% pollutant removal by LSA and LSPV respectively, inferring effective Cd removal.

From Figure 3, high average removal percentages were observed for Pb (>94.7%) and Zn (>98.1%). Cu removal was more moderate, ranging from 59.3% in traditional LS to 81.8% in LSPVZ media. Similarly to nutrient removal, traditional LS was
the worst performer, reporting mean differences of 13.2% for Cu, 3.9% for Pb and 0.8% for Zn when compared with the average removal by engineered media, Table 3.

Statistical analysis of metal removal by unvegetated media was undertaken for Cu, Pb and Zn (Cd was excluded due to lack of measurable values). Similar to nutrients, normality was not satisfied, therefore the nonparametric ANOVA Kruskal-Wallis H-test was used. Statistically significant differences in percentage removals was found for all metals between unvegetated media, Cu ($p = 0.0070$), Pb ($p = 0.00036$) and Zn ($p = 0.033$). This necessitated the Wilcoxon Rank-Sum pairwise comparison test between the media, with Fisher’s LSD test results depicted in Figure 3.

High removal percentages were observed due to filtration and adsorption being the major removal pathways for metals in stormwater biofilters (also see Barron et al. 2019). Although the majority of Cu was successfully removed, removals were constantly lower in comparison with Pb and Zn, similar to other findings (see Blecken et al. 2010). For improved Cu uptake, in addition to soil remediation, the introduction of plants create a direct uptake pathway (Muirdter et al. 2018). Phytoremediators have the ability to accumulate metals that are essential for growth and development, indicating the importance vegetation for optimised plant biofiltration (Dhir et al. 2009).

In the event of an intense precipitation event the average nutrient removal efficacy across all media decreased by 18.9% for NH$_3$-N and 32.9% for PO$_4^{3-}$-P, with a net increase of 182.9% observed for NO$_3$-N after 3 days of increased dosing. Metal removal was unaffected with no change in removal efficacy after the increased dosing period. Ten days post increased dosing, under typical volume irrigation, pollutant removal increased. This shows that pollutant remediation recovered post dosing stress. Statistical analysis showed no significant difference in removal efficiencies between media for each stormwater pollutant.

**Hydraulic performance**

Figure 4 depicts the varying surface IRs of the ten different media over time. The best performing unvegetated medium for the duration of the experiment was LSPVZ, averaging an IR of 161.1 mm/hr. In contrast, the worst performer was traditional LS, averaging 59.6 mm/hr, along with LSZ (92.64 mm/hr) and LSPV (99.55 mm/hr) below the recommended 100 mm/hr minimum biofilter requirement. The one-factor ANOVA analysing the surface IRs of the unvegetated media showed significant differences, indicating that at least one comparison between media to be significant, necessitating pairwise t-tests. In analysing the differences between the unvegetated media, traditional LS showed significant differences ($p \leq 0.05$) with all other media. Of interest, the effective infiltrating LSPVA and LSPVZ media also showed significant differences compared to each of the other media, except with each other.

In the presence of vegetation all media showed greater average surface IRs than the required 100 mm/hr. Similar to the best unvegetated performer, the best performing media in the presence of vegetation was LSPVZ, with an IR of 260.9 mm/hr.
From Figure 4, it is clear that vegetated media consistently outperformed unvegetated media across all combinations, infiltrating on average 71.9 mm/hr faster than the unvegetated media for the duration of the experiment. The pairwise comparison of surface IRs between unvegetated and vegetated media with time showed significant differences across all media combinations, manifesting significantly greater surface infiltration in biofilters equipped with plants.

In addition, the influence of vegetation is further illustrated by a surface IR increase with time for all vegetated media, producing on average 99.6 mm/hr or 60.9% infiltration increase over the 28 weeks. In contrast, after the same period infiltration decreased on average by 42.9 mm/hr or 26.7% in unvegetated media.

In the event of increased precipitation, simulated by increasing dosage from 0.63 to 9.41 L, the average surface IR of the media combinations decreased by 40.6 mm/hr and 55.1 mm/hr for unvegetated and vegetated biofilters respectively. Although the vegetated columns exhibited a larger loss in IR during these events, the columns still maintained a faster surface IR in comparison with the unvegetated columns. Statistically comparing the response by unvegetated with vegetated media under increased dosing, using the nonparametric Kruskal-Wallis H-test, showed significant differences. This finding supports the notion that biofilters equipped with vegetation are significantly more capable of sustaining infiltration during precipitation changes, as opposed to unvegetated biofilters. In addition to the contribution of non-traditional engineered media supporting infiltration, the specific root system of *Juncus effusus*, which is capable of extending downward or laterally, maintained adequate infiltration throughout fluctuating influent volumes. All of the engineered media exhibited greater capacity to endure runoff volumes from typical as well as intense precipitation events than traditional LS. Influent stormwater build-up was

![Infiltration rates (IRs) of unvegetated and vegetated media under alternating influent dosages with time.](http://iwaponline.com/wst/article-pdf/84/7/1715/948281/wst084071715.pdf)
observed above the growth media in unvegetated LS, LSZ, LSPV, LSV, LSP and LSPZ columns exposed to intense drip dosing over several hours, reporting IRs ranging from 59.6 to 116.1 mm/hr. For the unvegetated LSPA column, reporting the slowest surface IR in the absence of build-up (126.1 mm/hr), surface saturation was observed, an indication of water-logged soil. Thus, from the reported values in Figure 4, an IR above 126.1 mm/hr under the experimental dosing regime, prevented stormwater build-up, which may lead to overflow. The use of prolonged drip irrigation, the method adopted for experimental dosing, reduced the influent flow rate, hindering surface build-up whilst encouraging effluent discharge.

**Solids discharge**

Figure 5 illustrates the solids measured as turbidity and TS in the effluent of the ten media in the absence and presence of vegetation, at 20-day intervals for the duration of the 28-week experimental period. Analyses showed that the best and worst unvegetated media corresponded for both TS and turbidity. The best performer was LSPVA, producing final turbidity and TS values of 35 FTU and 78 mg/L respectively. In contrast, the worst unvegetated performer was LS, producing final values of 524 FTU and 422 mg/L for turbidity and TS respectively.

Analysing turbidity and TS with time (one-factor ANOVA), showed statistically significant differences for turbidity ($p = 0.0017$) and TS ($p = 0.0016$) between unvegetated media. With further comparison (pairwise t-test), showing only LSPVZ to be significantly different to all other media for both turbidity and TS. Although not significantly different to all other media, traditional LS differed significantly with the greatest number of media, as can be seen in the Fisher’s LSD test, Figure 5.

For vegetated media, the nonparametric Kruskal-Wallis H-test indicated statistically significant differences for turbidity ($p = 0.0037$) and no statistically significant differences for TS ($p = 0.42$). Therefore, the influence of vegetation on TS was not further assessed. For turbidity, the Wilcoxon Rank-Sum test indicated no statistically significant turbidity difference between individual unvegetated and vegetated media, implying a greater statistical influence by specific media on turbidity than vegetation. In other words, it seems that, although solids removal improved in the presence of vegetation, the media type was the primary influence on decreased turbidity and TS. Results were further analysed using Fisher’s LSD test (Figure 5).

**Figure 5** | Effluent TS and turbidity of unvegetated and vegetated media through time, with change in effluent clarity illustrated by photographic captures. From Fisher’s LSD test on turbidity, media with the same letter are not significantly different. LS, Loamy sand; LSP, Loamy sand + Perlite; LSPV, Loamy sand + Vermiculite; LSZ, Loamy sand + Zeolite; LSA, Loamy sand + Attapulgite; LSPV, Loamy sand + Perlite + Vermiculite; LSPZ, Loamy sand + Perlite + Zeolite; LSPA, Loamy sand + Perlite + Attapulgite + Zeolite; LSPVA, Loamy sand + Perlite + Vermiculite + Attapulgite.
From Figure 5, it is evident that effluent turbidity and TS of both unvegetated and vegetated media decreased with time, improving water clarity and reducing solids in stormwater runoff. The turbidity decrease across the media mixtures over the 28-week study period ranged from 564 to 943 FTU (\(\bar{x} = 808.7\) FTU) for unvegetated biofilters and 834 FTU – 991 FTU (\(\bar{x} = 904.8\) FTU) for vegetated biofilters, denoting average percentage decreases of 79.7% and 93.8% respectively. Similarly, the decrease in TS ranged from 697 – 844 mg/L (\(\bar{x} = 787.2\) mg/L) and 707 – 963 mg/L (\(\bar{x} = 831.2\) mg/L) in unvegetated and vegetated biofilters respectively, denoting percentage decreases of 79.6% and 89.1% respectively. Effluent solids removal was generally lower in the presence of vegetation, encouraging the removal of particulate organic nitrogen and phosphorous.

**Plant response**

Similar tussock growth (above-ground area and number of shoots) of *Juncus effusus* exposed to different media under non-polluted influent was observed, with no significant difference between media. Over the 28-week experimental period, tussock growth was most vigorous when exposed to LSZ and most reduced when exposed to traditional LS (Table 5), recording percentage growth of 300% and 82.8% respectively. Similarly root growth, as an established indicator of pollutant removal (Read et al. 2010), was assessed at harvest, reporting the greatest increase in length of the longest root when exposed to LSZ. Unsurprisingly, the length of the longest root showed a close relationship with infiltration (\(r^2 = 0.69\)).

From Table 5, initially the number of shoots outnumbered roots as opposed to roots outnumbering shoots at study completion, indicating a change in plant trait development. This trait development, consistent across media, is expressed by a change in the mean root:shoot ratio of 0.50 to 1.12, at initiation and study completion respectively. A root:shoot ratio increase indicates that although the above-ground portions (tussock area and shoots) of the plants were still experiencing an increase, the root systems were increasing at an even greater rate. Between the media combinations none were found to significantly influence above-ground or below-ground plant growth, thus no specific growth response in relation to media was observed.

In assessing the effect of polluted stormwater on plant development, the number of initial roots and shoots were compared with the number of final roots and shoots of *Juncus effusus* for both municipal and polluted stormwater treatments. The growth of new roots and shoots in plants receiving synthetic stormwater was constantly greater than plants under municipal dosing, with the stormwater acting as fertiliser to the vegetated biofilters. For roots, this increase can be seen in the initial mean synthetic stormwater (initial root) : municipal supply (initial root) ratio of 1.02 being smaller than the final mean synthetic stormwater (final root) : municipal supply (final root) ratio of 1.13 across all engineered media combinations. Similarly for shoots, the initial mean synthetic stormwater (initial shoot) : municipal supply (initial shoot) ratio of 1.09 was less than the final mean synthetic stormwater (final shoot) : municipal supply (final shoot) ratio of 1.14 across all media. The lack of noticeable nutrient and metal toxicity on the species’ plant growth rate (with species in reality thriving in synthetic stormwater) and historical pollutant removal performance, *Juncus effusus* and potential similar species are well equipped for urban load reduction (Ullah et al. 2015).

**Table 5** | Physiological trait development of *Juncus effusus* in different media

| Media | Tussock surface area (mm²) | Longest root (mm) | Number of roots | Number of shoots | Root:shoot |
|-------|---------------------------|------------------|----------------|-----------------|------------|
|       | Initial       | Final           | Initial       | Final           | Initial   | Final   |
| LS    | 1,590.43      | 4,901.67        | 150          | 248             | 23        | 60      | 0.50  | 1.11 |
| LSP   | 2,290.22      | 4,185.39        | 149          | 229             | 20        | 54      | 0.56  | 1.13 |
| LSZ   | 2,691.00      | 4,071.50        | 159          | 224             | 22        | 54      | 0.51  | 1.04 |
| LSA   | 1,256.64      | 5,026.55        | 161          | 265             | 23        | 75      | 0.55  | 1.04 |
| LSPV  | 1,809.56      | 4,185.39        | 167          | 238             | 22        | 70      | 0.51  | 1.09 |
| LSPVZ | 1,963.50      | 6,082.12        | 149          | 241             | 21        | 62      | 0.55  | 1.19 |
| LSPA  | 1,809.56      | 5,674.50        | 162          | 257             | 22        | 64      | 0.54  | 1.07 |
| LSPVA | 1,734.94      | 6,221.14        | 160          | 270             | 20        | 69      | 0.51  | 1.13 |

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Ranked engineered media for plant biofilter optimisation

Rating potential media for biofilter optimisation was based on performance across all relevant factors influencing GI efficacy and sustainability. The pollutant load removal, infiltration capacity and particulate discharge of each media was taken into account. Plant response was omitted due to similarity between engineered media. Individual performances were used to identify potential optimised biofiltration media capable of removing urban pollutants efficiently whilst sustaining local habitat and climate stress.

Generally, all included media combinations depicted desirable operational traits for effective urban stormwater remediation, making them suitable for use as plant biofilter growth media. For nutrients, although a nitrate increase was observed, effective ammonia-N and orthophosphate-P reduction was achieved. All media leached low levels of metal ions and produced very high removal efficiencies (>85%), with the exception of LS. Therefore, the three best media for general performance were LSPVA, LSA and LSPA. These media achieved high stormwater pollutant load removals, hindered possible sediment transport and maintained adequate infiltration rates under regular and intense dosing. Table 6 below can be used to determine media for targeted application, for example LSPVZ, which did not perform best across all factors, performed especially well with metal removal and infiltration and can contribute in scenarios requiring specific biofiltration.

The results highlight the variability of media performance, where media better equipped at improving a certain GI condition may perform worse in others. This variability highlights the importance of intricate biofilter planning and design, accounting for the target pollutant and the conditions of the recipient habitat in need of remediation.

**CONCLUSIONS**

The study investigated the nutrient and metal removal, infiltration rate, solids removal and plant response of nine engineered growth media combinations and one traditional loamy sand medium, towards the potential optimisation of urban plant biofiltration systems. Unvegetated column experiments were used to evaluate the pollutant removal efficiencies of the media, whereas vegetated *Juncus effusus* columns were used to assess the influence of vegetation on biofilter infiltration and solids removals.

All unvegetated engineered media effectively removed NH$_3$-N, PO$_4^{3-}$-P, Cd, Cu, Pb and Zn from synthetic urban stormwater runoff. For NO$_3$-N, leachate was observed across all media. During typical and intense precipitation events nutrient and metal removal efficiencies varied. A decrease in some nutrient removals was observed during increased dosing, whereas no differences were shown for metal removals.

The engineered media combinations maintained greater surface infiltration under varying influent dosages than traditional LS for the duration of the experiment, supporting their selection in clogging mitigation and overflow reduction. The implementation of infiltration enhancing media in small-scale GI offers the opportunity to decrease the required minimum size of biofilters, currently recommended at 2% of its catchment area, an attractive alternative for space-limited urban environments.

**Table 6 | Optimised engineered media ranking across all performance factors through time**

| Engineered media                                      | NR:MR:IR:TS:TU |
|------------------------------------------------------|----------------|
| Loamy sand + Perlite + Vermiculite + Attapulgite     | 1:2:2:1:1      |
| Loamy sand + Attapulgite                            | 5:5:4:2:2      |
| Loamy sand + Perlite + Attapulgite                  | 5:3:5:3:3      |
| Loamy sand + Perlite                                | 4:4:3:6:4      |
| Loamy sand + Perlite + Vermiculite + Zeolite        | 7:1:1:7:7      |
| Loamy sand + Vermiculite                            | 2:6:6:5:5      |
| Loamy sand + Perlite + Vermiculite                  | 6:8:9:4:6      |
| Loamy sand + Zeolite                                | 9:7:8:7:9      |
| Loamy sand + Perlite + Zeolite                      | 8:9:7:9:8      |
| Loamy sand                                          | 10:10:10:10:10 |

NR, Nutrient removal; MR, Metal removal; IR, Infiltration rate; TS, Total solids; TU, Turbidity.

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scenarios. In the presence of vegetation under varying influent dosages, the infiltration capacities of all biofilters significantly increased, supporting GI sustainability.

All media combinations effectively mitigated particulate deposition, improving effluent sedimentation and clarity. In the presence of vegetation, although insignificant, greater effluent clarity and sediment load reduction attributed to media stabilization and minimizing media movement was observed. This is particularly important during GI construction and establishment where phytostabilisation is threatened, leading to particulate discharge, erosion and clogging of urban drainage networks (Fletcher et al. 2013). Sediment accumulation leads to more frequent overflows and extended ponding time, reducing GI’s pollutant treatment capacity, resulting in watercourse and in-stream habitat degradation (Hatt et al. 2009; Le Coustumer et al. 2012).

The presence of above- and below-ground plant growth in all media indicated acceptable substrate in the experimental biofilter columns, encouraging vegetative establishment (Read et al. 2008). Between media there was no significant difference in plant functional response, supporting the inclusion of all combinations for use in biofilters. The root:shoot change showed a greater growth rate in the root system, ideal for phytoremediation favouring high root:shoot ratios due to enhanced contact with the pollutants in the rhizosphere (Payne et al. 2015). Although not significant, overall growth in plants receiving synthetic stormwater outperformed plants receiving municipal supply, with no signs of growth inhibition. This may be due to this experiment’s relatively low stormwater nutrient and metal toxicity and exclusion of other potential toxicants, which may be different in other conditions.

From the findings, the best performing media with regard to pollutant removal, infiltration, and solids discharge, were LSPVA, LSA and LSPA. Although ranking identified the best performing experimental media, selecting media for use in optimised GI projects must consider the recipient site’s target pollutant, conditions of the contributing catchment area affecting the minimum biofilter size, available and appropriate phytoremediator species, habitat and climate. Thus, in considering the conditions of the site in need of remediation, additional features may be required to optimise biofiltration, like the use of a saturated zone for enhanced nitrate removal (Barron et al. 2019).

In conclusion, the findings of this study provide important proof of concept for the application of engineered media in new and existing biofiltration systems for the removal of nutrient and metal pollutants from urban stormwater. The identified media aid in establishing, replenishing and maintaining treatment performance whilst resisting habitat and climatic stresses. Similar to previous studies, the results highlight the importance of vegetation in pollutant removal, infiltration and phytostabilisation (Henderson et al. 2007), in addition to contributing to microbial communities and socio-economic value (Hsu & Chao 2020). The use of engineered media improved pollutant removal, infiltration and particulate discharge, whilst supporting vegetative growth in a laboratory setting. Here engineered media as substrate tolerated increased dosing compared with traditional media mitigating overflow and pollutant runoff. Overflow allows runoff to evade treatment, picking up chemicals and pollutants along the way prior to discharge into urban waterways, deteriorating urban water quality, and diminishing the efforts of the urban water engineer.

Further research is required to assess the carrying capacity of engineered media in laboratory and field settings, particularly during periods of drought, to gauge the substrate’s potential moisture availability for root uptake and redox potential. Thus, determining at which infiltration rate specific engineered media impedes remediation and microbial activity. The size requirement of small-scale GI systems constructed with infiltration enhancing media, whilst maintaining treatment performance in the urban area must be determined, with a cost analysis included. Although the current study assessed general urban nutrient and metal remediation, additional contaminants of varying toxicity should be tested. In addition, evaluating biofilter response to a wider range of stresses and a greater variety of plant species would better equip the GI designer with knowledge regarding species’ ability to tolerate inundation, drought and biofilter media substrate. Finally, in order to assess the validity of biofilter performance, we propose budget calculations over pollutant removal, along the effluent probability method, with additional data captured from similar laboratory and field studies.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.
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