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Research article

Greywater treatment in a green wall using different filter materials and hydraulic loading rates

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ABSTRACT

Green walls in urban environments can be both an aesthetic feature and be of practical use in greywater treatment. This study evaluates the effect of different loading rates (4.5 l/d, 9 l/d, and 18 l/d) on the efficiency of treating actual greywater from a city district in a pilot-scale green wall with five different filter materials as substrates (biochar, pumice, hemp fiber, spent coffee grounds (SCG), and composted fiber soil (CFS)). Three cool climate plant species, *Carex nigra, Juncus compressus, and Myosotis scorpioides*, were chosen for the green wall. The following parameters were evaluated: biological oxygen demand (BOD), fractions of organic carbon, nutrients, indicator bacteria, surfactants, and salt. Three of the five materials investigated – biochar, pumice, and CFS - showed promising treatment efficiencies. The respective overall reduction efficiencies of BOD, total nitrogen (TN) and total phosphorus (TP) were 99%, 75%, and 57% for biochar; 96%, 58%, and 61% for pumice; and 99%, 82% and 85% for CFS. BOD was stable in the biochar filter material with effluent concentrations of 2 mg/l across all investigated loading rates. However, higher loading rates had a significantly negative effect on hemp and pumice for BOD. Interestingly, the highest loading rate (18 l/d) flowing over pumice removed the highest levels of TN (80%) and TP (86%). Biochar was the most effective material in removing indicator bacteria, with a 2.2–4.0 Log_{10} reduction for *E. coli* and enterococci. SCG was the least efficient material, giving a higher BOD in the effluent than in the influent. Therefore, this study presents the potential of natural and waste-derived filter materials to treat greywater effectively and the results can contribute to the future development of nature-based greywater treatment and management practices in urban areas.

1. Introduction

Domestic wastewater can be divided into two fractions: blackwater and greywater. The toilet fraction (urine and feces) is called blackwater, whereas greywater is generated from the kitchen, laundry, showers/ baths, and hand basins. More than 70% of the total domestic wastewater is greywater, but it can be up to 90% if vacuum toilets are used (Hernández Leal et al., 2011). Moreover, greywater contains lower levels of nutrients (nitrogen and phosphorus), pathogens (e.g. *Escherichia coli* (*E. coli*)) and organic matter as measured by the Biological Oxygen Demand, (BOD), or Chemical Oxygen Demand (COD) compared to total domestic wastewater (Shaikh and Ahammed, 2020). In addition, greywater quality and quantity can vary across households depending on the number of users and their domestic habits, for example, concentrations in the ranges of 20–518 mg/l of BOD, 4.0–15 mg/l of total nitrogen (TN), and 0.2–4.0 mg/l of total phosphorus (TP) (Boyjoo et al., 2013; Oteng-Peprah et al., 2018b) have been reported. Many previous studies have therefore used artificial greywater with consistent quality; however, this may not provide a realistic understanding of the treatment performance. These characteristics allow the potential to decentralize the treatment of source-separated greywater (Opher and Friedler, 2016) before discharging it into the environment. Treated greywater can then be a source of water for non-potable uses, such as agricultural irrigation (Li et al., 2009; Oteng-Peprah et al., 2018a).

Green walls are becoming a popular aesthetic aspect of urban development; they have positive effects on air quality, noise reduction, and the immediate ambient climate, in addition to providing a green environment (Ascione et al., 2020). As a nature-based solution, a green wall can be an energy-efficient and low-maintenance decentralized treatment system for greywater (Boano et al., 2020). However, research on green walls for treating greywater is limited using this type of representative mixed greywater. Most of the existing studies have been

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conducted in warmer climates (Masi et al., 2016; Pradhan et al., 2019; Prodanovic et al., 2017; Zraunig et al., 2019).

Previous studies have shown that filter material is one of the most important factors influencing the treatment efficiency of a green wall. Different factors have been used in the selection of substrate material including physical factors such as porosity; practical considerations (whether materials are locally available and/or naturally occurring); environmental concerns (using suitable recycled materials) (Pradhan et al., 2020). Some of the filter materials investigated in earlier studies include perlite (Ø 1–2 mm), coco coir, lightweight expanded clay (LECA) (Ø 4–10 mm), and sand (Masi et al., 2016; Prodanovic et al., 2017). Pumice, a material with similar characteristics as LECA or perlite, has not been investigated previously. In addition, new innovative materials have also been investigated such as spent coffee grounds (SCG) (Ø <0.5 mm) and date seeds (Pradhan et al., 2020), crushed tiles (Ø 4–8 mm) and textile fibers (Galvão et al., 2022), biochar (Ø 5–10 mm) and composts (Ø 0.5–25 mm) derived from organic waste (e.g. sawdust, pruning) (Boano et al., 2021; Lakho et al., 2021) and hydrochar derived from organic waste using hydrothermal carbonization (Alqadami et al., 2023). Nevertheless, biochar, composts, SCG, and natural fibers like hemp, which can be an alternative to coco coir or textile fibers, have not yet been investigated extensively in green walls for greywater treatment. Moreover, substrate materials need to provide enough hydraulic retention so that greywater can infiltrate sufficiently to prevent clogging. Mixing different substrate materials with complementary properties has therefore been suggested as a method to optimize retention time, infiltration capacity, and treatment efficiency. Masi et al. (2016) tested two materials, coco coir, and sand, mixed with LECA in the volume ratio of 1:1 to increase the retention time, reduce infiltration rate and enhance biological treatment. However, because higher proportions of materials such as coco coir or sand can have a negative effect on the infiltration capacity, leading to frequent clogging of the system, Prodanovic et al. (2018) studied different mix ratios of filter materials and found an effective mix to be a 1:2 (by volume) ratio of perlite to coco coir, which provided sufficient infiltration as well as biological treatment.

Another important factor influencing the treatment efficiency of green walls is the hydraulic loading rate (HLR) of greywater (Pradhan et al., 2020; Prodanovic et al., 2017). In previous studies, a range of different loading rates has been employed, including 1.0 l/d (32 $l/m^2/d$) (Dalahmeh et al., 2014; Karlsson et al., 2015); 98 l/d (36 $l/m^2/d$) (Dal Ferro et al., 2021); 2.5–5.0 l/d (55–110 $l/m^2/d$) (Fowdar et al., 2017); 3 l/d (382 $l/m^2/d$) (Prodanovic et al., 2018); 0.5–1.5 l/d (79–236 $l/m^2/d$) (Pradhan et al., 2020); and 4 l/d (100 $l/m^2/d$) (Bakheet et al., 2020). One study has tested loading rates as high as 750–1400 l/d (100–1900 $l/m^2/d$) (Zraunig et al., 2019). The calculated volumetric loading rate, with respect to substrate volume, ranged between 0.05 $l/l_f/d$ (Karlsson et al., 2015) to 2.3 $l/l_f/d$ (Dal Ferro et al., 2021), where l_f is substrate volume. In addition to the HLRs, the organic loading rate, which varies with the source of greywater, also influences the treatment efficiency. The organic load in previous studies ranged from 5.7 g $BOD/m^2/d$ (Fowdar et al., 2017) to 76 g $BOD/m^2/d$ (Dalahmeh et al., 2014).

Vegetation is another aspect of a green wall system. This not only adds aesthetic value but also contributes to the treatment of greywater. The performance, especially regarding nitrogen removal, of the filter materials in green wall systems has been shown to improve when it is vegetated, (Fowdar et al., 2017; Pradhan et al., 2019; Prodanovic et al., 2019a, 2019b). The water demand of green walls is also increased through uptake and evapotranspiration by plants during different climatic conditions (Prodanovic et al., 2019a, 2019b).

The aim of this study was to evaluate the effect of different hydraulic loading rates on the efficiency of green walls structured with five different filter materials (naturally occurring and waste-derived) used as substrates, in treating actual greywater from a city district. In addition, three cool climate plant species were planted in the green wall, and assessed their growth and resilience during the experimental period.

2. Materials and methods

2.1. Green wall setup

The study was carried out at the testbed facility RecoLab in Helsingborg, Sweden, which has access to source-separated greywater (800 PE at the time of the study) generated from a nearby city district, comprising five residential buildings, an office building, two restaurants, and two beauty parlors. The commercially available green wall module "*Gro-wall® 4.5*" (Atlantis, Australia) made from 85% recycled polypropylene was used. The wall had 36 pots of dimensions 375 mm × 225 mm x 220 mm (length, width, depth) and a 6 l capacity per pot (Fig. 1). The surface area of filter materials in each pot was approximately 0.084 m^2. Following Prodanovic et al. (2020), a column of three pots was considered as one treatment configuration, providing a total of 18 l of substrate volume. Three plants of each species were planted in every configuration, and each pot of a configuration was planted with three plant plugs of the same species. Each filter material configuration was replicated three times and their arrangement in the wall was randomized (Supplementary Material, Table A1).

Five filter materials were selected as the substrates for this green wall study: *pumice*, *biochar*, *hemp fiber*, *spent coffee grounds (SCG)*, and *composted fiber soil (CFS)*. Pumice was used as a coarse inorganic material in every pot to enhance the infiltration capacity of the other filter materials. In addition, three configurations comprising only pumice were included in the setup as a control. In other configurations, the filter materials biochar, hemp, SCG, and CFS were mixed with pumice in a 2:1 ratio by weight. The material mixes in the respective pots were biochar: pumice 1700:850 g, hemp:pumice 500:250 g, SCG:pumice 1500:750 g, CFS:pumice 2500:1250 g, and pumice only 3700 g. The different total weight of the filter materials was calculated in a way so that each pot was is filled to the total volume of 6 L. To avoid clogging at the bottom of the pots, a 250g pumice layer was used in all pots." To avoid clogging at the bottom of the pots, a 250g pumice layer was used in all pots. Hereafter, the material mixes will be referred to without mentioning pumice, e.g. hemp/pumice mix as *hemp*. The term *pumice* will refer to the configurations comprising only pumice.

The plant species were selected according to the following criteria: they should (i) be of a size that fits the wall structure and pots, (ii) have a shallow root system, (iii) tolerate constant wet conditions, (iv) require low maintenance and (v) tolerate greywater, which has high alkalinity and salt concentration from detergents, softeners, personal care products, etc. Based on those criteria, the species *Juncus compressus*, *Carex nigra*, and *Myosotis scorpioides* were chosen. A high-intensity discharge lamp (600 W) with a Photosynthetic Photon Flux Density of 1098 μmol/m^2/s was placed at a distance of 2 m from the green wall as the light source for 14 h s per day (6 a.m.–8 p.m.).

2.2. Hydraulic loading rates (HLR) and dosing regime

Previous studies indicated that low HLR provides effective treatment (Fowdar et al., 2017; Pradhan et al., 2020; Prodanovic et al., 2020). A loading rate of 4.5 l/d was used as the lowest loading rate, corresponding to an HLR of 54 $l/m^2/d$ (0.25 $l/l_f/d$ volumetric loading rate). The 54 $l/m^2/d$ resulted in an organic load of 10.8 g $BOD/m^2/d$ (assuming an average of 200 mg/l of BOD) which was similar to the lower organic load of 11.6–13 g $BOD/m^2/d$ used in the previous studies by Dalahmeh et al. (2014) and; Zraunig et al. (2019). For the higher loading rates, this was doubled and redoubled to obtain loading rates of 9 l/d and 18 l/d (corresponding to 0.5 $l/l_f/d$ and 1.0 $l/l_f/d$), respectively. The HLR for 9 l/d and 18 l/d was therefore 108 $l/m^2/d$ and 216 $l/m^2/d$ respectively.

The raw greywater was pre-treated in a two-chamber pre-sedimentation tank, the volume of each chamber being 210 l (Fig. 1). A 12-channel Ismatec ISM932 peristaltic pump was used to load the upper pots of each configuration with greywater. The water percolated through the

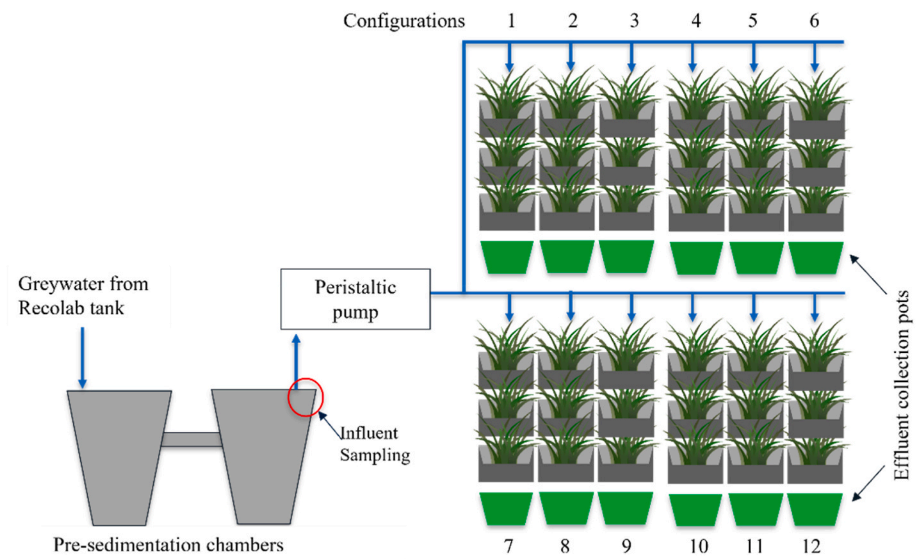

Fig. 1. Experimental setup of the green wall. The red circle indicates the influent sampling point. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

substrate and then through the perforated bottoms of each pot, to the pots below. The effluent was collected in 20 l HD-PE plastic containers (Fig. 1).

The green wall was initially irrigated with tap water for two weeks, followed by six weeks with greywater at a loading rate of 4.5 l/d before the first sampling event. The use of tap water in the initial phase was to allow the plants to establish in the filter materials and also wash out any fine particles present from the filter materials. The idea of the establishment phase with tap water and greywater was adopted from the studies by Dalahmeh et al. (2012) and Prodanovic et al. (2019a). The wall was irrigated twice a day for 8 h, each followed by 4 h of rest. Following sequence treatment, four sampling events were carried out from 1 November 2021 to 14 January 2022 on the configurations with pumice, biochar, and hemp. Due to practical issues and unsuitable treatment performances, SCG was only tested with 4.5 l/d, after which the pots were replaced with CFS. After the same establishment period (two weeks of tap water and six weeks of greywater) as the other materials, with a 4.5 l/d loading rate, the effluent from the CFS pots was sampled in Feb 2022. The change and establishment periods of the loading rates and change of materials are presented in Fig. 2.

2.3. Sampling

During each sampling event, influent and effluent samples were collected and sent for analyses on three consecutive days (Fig. 2). Effluent from each configuration, which was collected in the 20 l container (Fig. 1), was shaken well and poured into a beaker, stirred, and sub-sampled into bottles for subsequent analyses of organic and inorganic matter, nutrients, surfactants, and indicator bacteria (Table 1). 4.5 influent greywater sample was taken manually from the second pre-sedimentation tank (Fig. 1). For the analysis of dissolved phosphorus and dissolved organic carbon, samples were filtered through 0.45 μm fiberglass filters prior to the analyses. Before each sampling day, the effluent pots and the containers were rinsed thoroughly using tap water. Photos were taken after each sampling occasion to assess the growth of the plants and the overall condition of the green wall (Supplementary Material, Figure A1–A5).

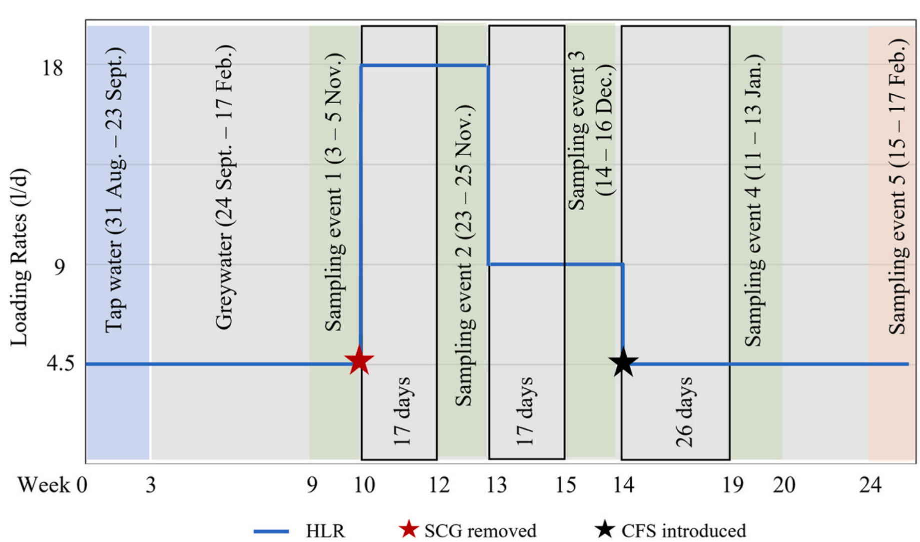

Fig. 2. Establishment periods (days) between each sampling event and loading rate change during the experimental timeline. At the start of the experiment, the filter materials pumice, biochar, hemp, and SCG were used. Sampling event 5 was only for the composted fiber soil (CFS) filter material that was introduced in week 14.

Table 1
Parameters analyzed and analytical methods used.

Parameter	Method	Title of method
TSS	SS-EN 872	Water quality - Determination of suspended solids - Method by filtration through glass fiber filters
BOD_7	SS-EN ISO 5815–1:2019	Water quality - Determination of biochemical oxygen demand after n days (BODn) - Part 1: Dilution and seeding method with allylthiourea addition
COD (Cr)	ISO 15705:2002	Water quality - Determination of the chemical oxygen demand index (ST-COD) - Small-scale sealed-tube method
TOC	SS-EN 1484	Water analysis - Guidelines for the determination of total organic carbon (TOC) and dissolved organic carbon (DOC)
TN	SS-EN 12260:2004	Water quality - Determination of nitrogen - Determination of bound nitrogen (TNb), following oxidation to nitrogen oxides
TP	SS-EN ISO 15681–2:2018	Water quality - Determination of orthophosphate and total phosphorus contents by flow analysis (FIA and CFA) - Part 2: Method by continuous flow analysis (CFA)
NH_4–N	ISO 15923–1:2013	Water quality – Determination of selected parameters by discrete analysis systems – Part 1: Ammonium, nitrate, nitrite, chloride, orthophosphate, sulfate and silicate with photometric detection
Sodium (Na)	ISO 11885	Water quality - Determination of selected elements by inductively coupled plasma optical emission spectrometry (ICP-OES)
Chloride (Cl)	SS-EN ISO 10304–1:2009	Water quality - Determination of dissolved anions by liquid chromatography of ions - Part 1: Determination of bromide, chloride, fluoride, nitrate, nitrite, phosphate and sulfate
E. coli	SS028167-2 MF	Coliform Bacteria, Thermotolerant Coliform Bacteria and *Escherichia coli* in Water - Determination with the Membrane Filtration Method (MF)
Enterococci	SS-EN ISO 7899-2	Water quality - Detection and enumeration of intestinal enterococci - Part 2: Membrane filtration method
Surfactants (LAS)	CSN ISO 16265	Water quality - Determination of the methylene blue active substances (MBAS) index - Method using continuous flow analysis (CFA)

2.4. Analyses

Quantification and analyses of organic matter (BOD, COD, TOC), nutrients (TN and TP), total suspended solids (TSS), sodium, chloride, and indicator bacteria were outsourced to an accredited laboratory, SGS Analytics, Sweden. The anionic surfactant, linear alkylbenzene sulfonate (LAS), was analyzed by the external accredited laboratory ALS Scandinavia. The methods used are summarized in Table 1 pH, conductivity, and turbidity were measured on-site. The pH was measured using a WTW pH3110 pH meter and SenTix®41 electrode and conductivity (μS/cm) was measured using a WTW Cond 3110 m with TetraCon®325 electrode. Turbidity (FNU) was measured using a Hach 2100Qis turbidimeter.

2.5. Statistical methods

The influent and the effluent concentrations did not follow normal distributions. Therefore, the non-parametric Kruskal-Wallis test was used to assess filter material performances and the effect of hydraulic loading rates on effluent concentrations. In addition, the post-hoc Mann-Whitney test with Bonferroni correction was used to assess the treatment efficiencies between filter materials at different hydraulic loading rates. The effect of initial and final 4.5 l/d was compared with a Wilcoxon signed-rank test (Mann-Whitney test without Bonferroni correction). The data were analyzed using IBM SPSS software (28.0 version) with a significance level of 5%.

3. Result

3.1. Overall treatment by the filter materials

The efficiencies of the filter materials - hemp, pumice, and biochar – at treating the greywater across all loading rates during the 19-week experiment were evaluated according to the concentrations of the various contaminants in their effluents. The Kruskal-Wallis test showed that the efficacy of the filter materials varied significantly for all contaminants except sodium and chloride. In terms of organic matter, pumice and biochar were more effective in BOD reduction (by 96% and 99%, respectively) compared to hemp (85%) (Fig. 3). Similar efficiencies were observed for COD reduction and removing TOC. TSS removal by biochar was consistent (>95%) which was significantly higher than the pumice and hemp. Although the influent concentrations of surfactants were generally low (<1 mg/l, see supporting information), surfactants were efficiently removed by all materials, with a mean removal rate of between 75% (hemp) and biochar (96%) (Fig. 3).

The biochar material achieved the highest mean TN removal (75%) whereas both hemp and pumice removed 58% of TN on average (Fig. 3). However, although hemp was more effective than pumice or biochar at removing TP (66%, 61%, and 57%, respectively) (Fig. 3), there were no significant differences in the TN and TP effluent concentrations between hemp and pumice; neither did the TP effluent concentrations differ between pumice and biochar according to the Kruskal-Wallis test.

SCG and CFS were only tested at a loading rate of 4.5 l/d for a period of 8 weeks each (Fig. 2). The effluent from the SCG configurations showed high concentrations of organic material (e.g., 600–1100 mg/l of BOD, see supporting information), which was much higher than the influent concentrations (68–170 mg/l, see supporting information). SCG was only effective at removing TP with a mean removal rate of 41%, which was higher than the biochar (31%) under the same conditions. In contrast, the CFS (also tested at a loading rate of 4.5 l/d only) showed efficient treatment with a high reduction of BOD (99%), TN (82%), and TP (85%), and with effluent concentrations of 3 mg/l of BOD, 3.1 mg/l of TN and 0.3 mg/l of TP (see supporting information).

3.2. Effect of loading rates on the treatment organic matter

Based on the influent BOD, the organic loads during the different loading rates (4.5, 18, 9, and 4.5 l/d) were 6.6, 55.5, 25.2, and 18.0 g

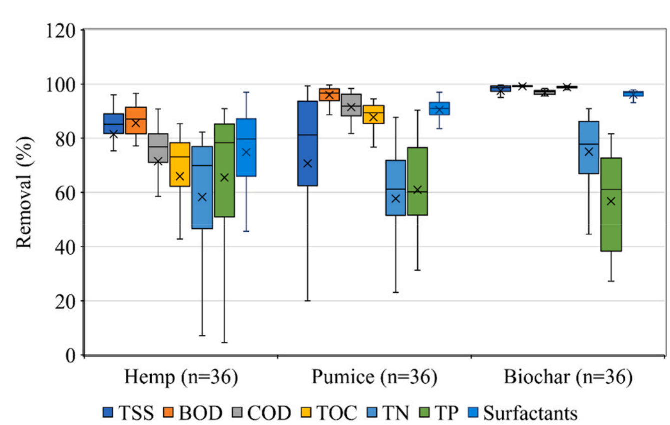

Fig. 3. Removal efficiencies of different parameters observed by the filter materials hemp, pumice, and biochar, calculated using results from all studied loading rates (n = 36 for each material, i.e., 3 samples each from the 3 configurations and at 4 different loading rates).

BOD/m²/d, respectively. The varying influent BOD values across the different loading rates seemingly did not affect the treatment capacity of the materials (Fig. 4). However, the increase in loading rate from 4.5 to 18 or 9 l/d showed a significant positive effect on the BOD effluent concentrations (i.e. the BOD concentrations increased with increasing HLR) from the hemp and pumice configurations, while the biochar configurations were not significantly affected (Table 2). The treatment of BOD by the biochar material was very stable, with a mean effluent concentration of 2 mg/l across all the loading rates (Fig. 4). For pumice, the mean BOD values for the effluent were significantly higher during the high loading rates (17 mg/l at 8 l/d) than at the lower loading rates (5 mg/l at 4.5 l/d) (Fig. 4). Treatment efficiency varied across the different hemp configurations, e.g. during 9 l/d (Fig. 4). However, the BOD of effluent from hemp and biochar materials during the initial and final 4.5 l/d loading rates did not differ significantly from each other (Wilcoxon signed-rank test); and for the pumice material, the BOD improved significantly (Wilcoxon signed-rank test) over time from weeks 9–19.

The removal of TOC was mostly associated with the treatment of the particulate fraction which could be through biological degradation or adsorption onto the filter materials (Fig. 5). Moreover, the dissolved organic carbon concentrations in the effluent from hemp configurations (ranging from 21 mg/l to 39 mg/l) were significantly higher than from pumice or biochar configurations, which ranged from 8 to 16 mg/l and 1–2 mg/l, respectively, across all loading rates (Fig. 5).

3.2.1. Nutrients

Among the various substrates, biochar was significantly (Kruskal-Wallis test) effective at removing nitrogenous compounds (Fig. 6) although it varied significantly between the different loading rates (Table 2). The highest removal of TN by biochar material (>85%) was observed during the 18 l/d loading rate and with a mean effluent concentration of 2 mg/l (Fig. 6). The later change of loading rates to 9 l/d and 4.5 l/d reduced the removal rate to 78% and 75%, with effluent concentrations of 3.2 mg/l and 3.9 mg/l, respectively (Fig. 6). Similarly, for pumice, a higher loading rate of 18 l/d increased the treatment of TN (Table 2) and removed 80% of TN (Fig. 3) with an effluent concentration of 3.4 mg/l (Fig. 6). During the other loading rates, the effluent from the pumice material achieved TN concentrations ranging between 7.2 mg/l and 8 mg/l (Fig. 6). No significant difference (Kruskal-Wallis test) in mean effluent concentration from pumice material was observed between the initial 4.5 l/d and the 9 l/d loading rate. In the case of hemp, the TN concentrations in effluent were similar during the initial 4.5 l/d, 18 l/d, and 9 l/d loading rates when the concentration in effluent ranged from 4 mg/l to 4.7 mg/l until a drastic deterioration in treatment was observed at the final 4.5 l/d rate when the concentration rose to 13 mg/l (Fig. 6). An increase in HLR showed a decrease in TN effluent concentration by the hemp configurations (Table 2). The N removal by hemp ranged from 69% to 75% during the 4.5 l/d, 18 l/d, and 9 l/d loading rates, and fell to 18% during the final 4.5 l/d (Fig. 3). However, the mean TN concentration in the effluent from the biochar material decreased significantly from 6.3 mg/l to 3.9 mg/l, between the initial and final 4.5 l/d loading rates, indicating an improvement of treatment by this material over time.

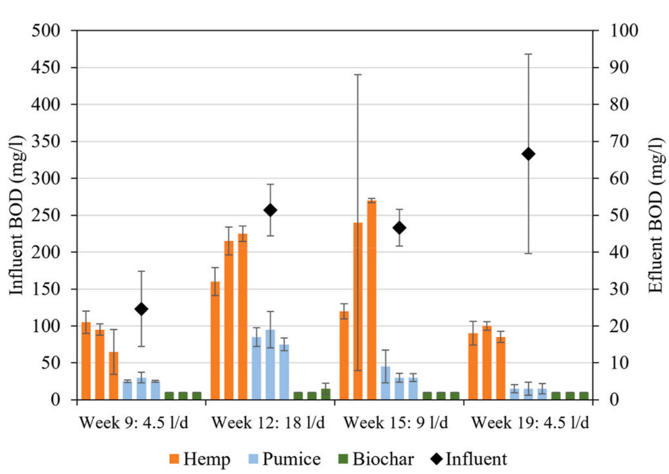

Fig. 4. Influent and effluent BOD from the hemp, pumice and biochar configurations observed at the different loading rates. Error bars show the standard deviations. Each material replicate is shown as one column in the chart.

Some TN removal by the different configurations was associated with the separation of the particulate phase of the organic nitrogen (org-N). Furthermore, a large fraction of ammonium was either evaporated as ammonia and/or nitrified (clearly seen with pumice and biochar), and possibly denitrified since the TN was significantly lower in the effluent and was mostly in the form of nitrite/nitrate (Fig. 6).

For the hemp configuration, the NH_4–N in the influent was all nitrified or denitrified, since a large share of TN was removed and no $NO_{2,3}$-N was observed in the effluent during the first three loading rates. Ammonia losses were considered to be of minor importance since the effluent pH was in the range of 7.4–8.2 (see supporting information). The mean effluent org-N concentrations from the hemp material during each of the loading rates (4.5 l/d, 18 l/d, 9 l/d, and 4.5 l/d) were 4.6 mg/l, 4.2 mg/l, 3.9 mg/l, and 4.7 mg/l, respectively (Fig. 6). However, a higher concentration of ammonium was released in addition to the org-N during the final 4.5 l/d, especially from one configuration, in which the mean effluent TN concentration was apparently higher than the mean influent concentration (Fig. 6).

In the pumice configurations, effective degradation and nitrification of org-N and NH_4–N to soluble $NO_{2,3}$-N was observed (Fig. 6). During the first 4.5 l/d loading rate, 7.9 mg/l org-N in the influent was reduced to <0.7 mg/l, while 8.1 mg/l NH_4–N was converted to between 6.8 mg/l and 7.5 mg/l $NO_{2,3}$-N (Fig. 6). Similar phenomena were observed in the case of 9 l/d and the final 4.5 l/d loading rates. However, during the 18 l/d loading rate, 12.6 mg/l org-N was reduced to <3 mg/l in the effluent, while most of the NH_4–N was nitrified, releasing <1 mg/l NH_4–N and $NO_{2,3}$-N in the effluent (Fig. 6).

Effective nitrification of the NH_4–N was prevalent in the biochar configurations during all four loading rates, where org-N was completely removed. During the 18 l/d loading phase, the mean effluent TN concentration from biochar configurations was lowest (<2 mg/l) with the release of small amounts of NH_4–N (0.2 mg/l – 0.9 mg/l) (Fig. 6). Apart from the first 4.5 l/d loading rate, the mean effluent concentrations of TN from biochar configurations were <5 mg/l.

The treatment of phosphorus (P) in the hemp configurations was significantly more efficient compared to the pumice and the biochar configurations, which is reflected by the low effluent concentrations during the first three loading rates (Fig. 6) (0.3 mg/l–0.4 mg/l). The TP removal by hemp at 4.5 l/d, 18 l/d, and 9 l/d loading rates was 85%, 84%, and 75% respectively. However, similar to the effects of N, the treatment of P also deteriorated during the final 4.5 l/d loading when 18% was removed to give an effluent concentration of 1.8 mg/l (Fig. 6). Increasing HLR resulted in more effective treatment of P in the pumice and biochar materials, as indicated by decreasing effluent concentration at the higher HLRs (Table 2). The most efficient treatment of TP was by pumice at the high loading rate (18 l/d) achieving a mean effluent concentration of 0.3 mg/l (Fig. 6) and a removal rate of 86% (Fig. 3). The mean effluent concentration from pumice ranged between 0.8 mg/l and 1.1 mg/l during the other loading rates (Fig. 6) with TP removal ranging between 44% and 62%. With biochar, the TP effluent concentrations decreased significantly (Kruskal-Wallis test) across all the different loading rates during the experimental period. The mean TP effluent concentration was reduced from 1.5 mg/l at the beginning to 0.5 mg/l by the end of the experiment (week 19, Fig. 6). Compared to pumice and biochar, hemp removed more dissolved P, except during the final 4.5 l/d. The mean particulate P removal by hemp during the different loading rates ranged between 73% and 86% whereas pumice

Table 2
Effect of the hydraulic loading rate on the effluent concentrations achieved with the different filter materials determined using the Kruskal-Wallis test for the loading rates of 4.5, 9, and 18 l/d. A statistically significant increase (+) or decrease (−) in the effluent concentrations of the greywater quality parameters with the increase in the loading rate is shown. (0) indicates no statistically significant change in the effluent concentrations across the tested hydraulic loading rates.

	TSS	BOD	TN	TP	Sodium	Chloride	Surfactants	*E coli*	Enterococci
Hemp	+	+	–	0	–	0	+	+	0
Pumice	+	+	–	–	–	0	+	+	0
Biochar	0	0	–	–	–	0	+	+	+

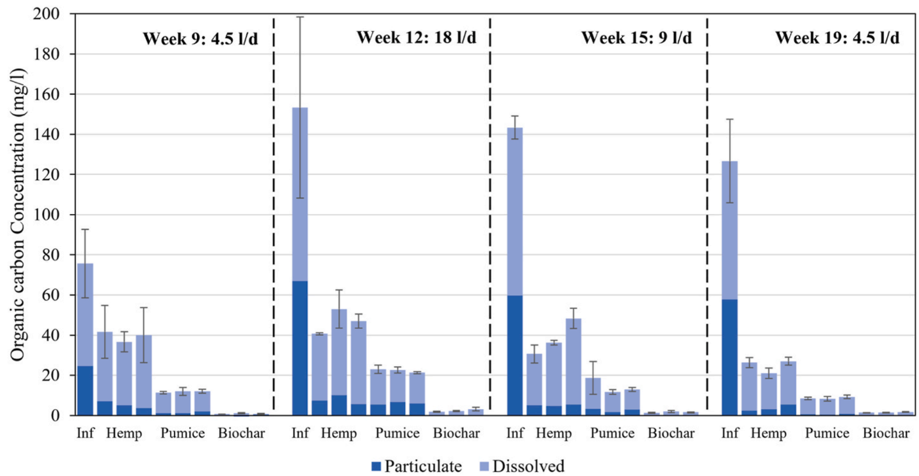

Fig. 5. Mean (n = 3) particulate and dissolved organic carbon concentrations in the influent greywater and effluents from the different filter material configurations during different hydraulic loading rates. Standard deviations are shown with error bars.

and biochar achieved >90% removal.

3.2.2. Microorganisms

High concentrations of the indicator bacteria *E. coli* and enterococci were detected in the influent and the effluents from the green wall. In most cases, the influent *E. coli* concentrations were >100,000 cfu/100 ml (Supporting information). Enterococci concentrations were sometimes >100,000 cfu/100 ml but also ranged between 7800 and 42,000 cfu/100 ml (Supporting information). Similar high concentrations of *E. coli* and enterococci were observed in the effluents, especially during the high loading rate (18 l/d and 9 l/d). In some cases, effluent concentrations were <10 cfu/100 ml (e.g. biochar configurations) during the low loading rate of 4.5 l/d (Supporting information). The dilution of the sample before analysis was insufficient, hence the results obtained were not quantifiable above this level. Therefore, when such quantified concentrations were missing, the upper and lower quantification limits were applied to calculate the lowest possible reduction of *E. coli* and enterococci (Fig. 7 and supporting information).

Among the five materials investigated, biochar caused the highest reduction of *E. coli* and enterococci at all loading rates (Fig. 7). During the initial 4.5 l/d loading rate, biochar had a reduction range of 2.2–4.0 Log_{10} for both *E. coli* and enterococci (Fig. 7). However, the reduction by biochar decreased significantly during the high loading rate (Table 2); nevertheless, its mean reduction was higher than for either hemp or pumice.

Although hemp obtained a relatively high reduction of *E. coli* (2.1 Log_{10}) during the initial 4.5 l/d, the reduction capacity dropped significantly to < 0.1 Log_{10} during the rest of the loading rates (Fig. 7, Table 2). A similar trend of *E. coli* reduction was observed with the pumice material. CFS also effectively removed both *E. coli* and enterococci, with the highest reduction being 3.8 Log_{10} and 2.9 Log_{10} respectively; but the mean reduction was lower than noted for either hemp or pumice (Fig. 7). For the investigated initial 4.5 l/d loading rate, SCG was the poorest performing material at reducing *E. coli* and enterococci.

3.2.3. Salinity

The concentrations of sodium and chloride in the influents and the effluents did not differ (Kruskal-Wallis test) across the studied materials. The sodium concentrations in the influent greywater were in the range of 69–76 mg/l and the influent chloride concentration was in the range of 58–61 mg/l. The influent sodium concentration was much lower than either the 118–140 mg/l range reported for the un-treated greywater in developing countries (Oteng-Peprah et al., 2018b) or the 144 mg/l reported in Sneek, the Netherlands (Hernández Leal et al., 2011). However, the influent chloride concentration in this study was higher than the maximum reported concentration of 50 mg/l in the greywater of developing countries (Oteng-Peprah et al., 2018b). The effluent concentrations of sodium from all the filter materials ranged between 68 mg/l and 79 mg/l, which is lower than the 100 mg/l discharge limit recommended by the World Health Organization (WHO, 2006). Moreover, the effluent concentration of chloride from the filter materials was slightly higher than the influent (60–66 mg/l) but lower than the 140 mg/l discharge limit recommended in Ghana as reported by Oteng-Peprah et al., 2018b.

3.3. Vegetation growth

The growth and survival of the plant species were assessed through visual observations. Most of the *Carex nigra* plants in the green wall grew and survived throughout the entire experimental period, indicating that it was resilient to greywater irrigation and filter material (Supplementary Material, Figs. A2 and A3). The *Juncus compressus* plants were also relatively resilient as new leaves were often observed every few weeks; however, the plants turned brown and dried over time (Supplementary Material, Figs. A2 and A3). The *Juncus compressus* species seemed to grow better in the hemp material than in either the pumice or biochar. *Myosotis scorpioides* grew well in all the materials during the establishment period with tap water (Supplementary Material, Fig. A2). However, its growth deteriorated and the plants started to die when the greywater was introduced (Supplementary Material, Fig. A2).

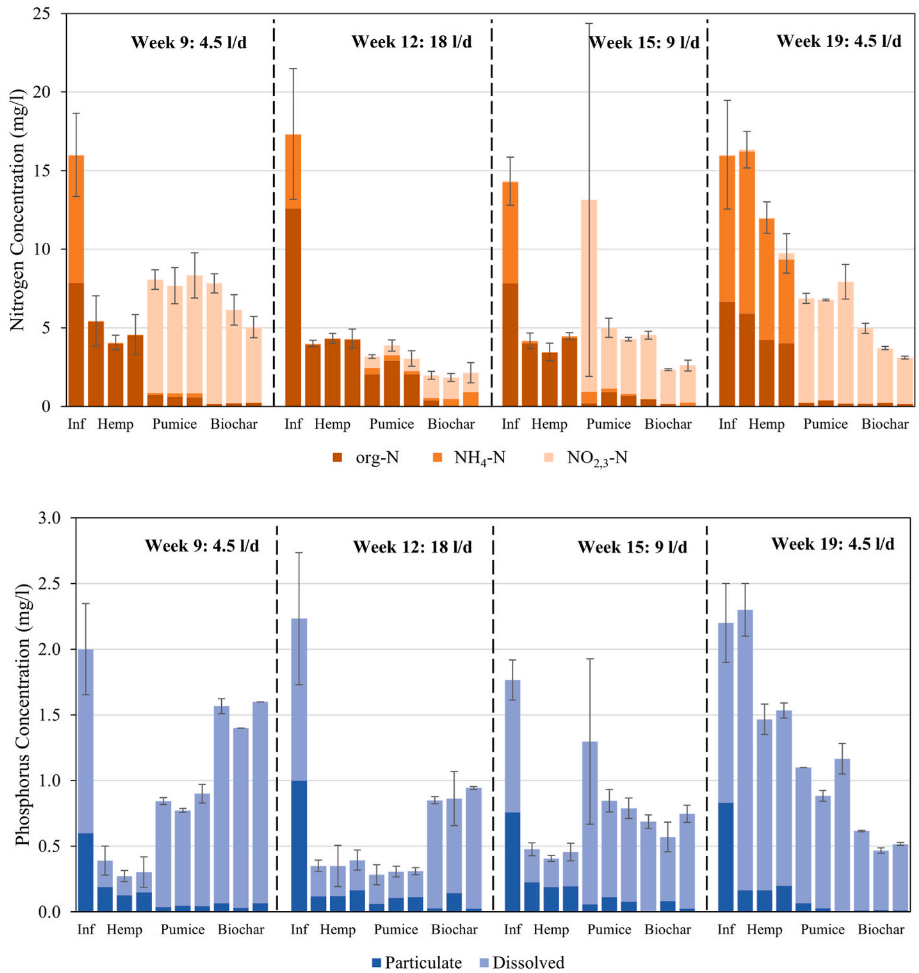

Fig. 6. Top: Fractions of total nitrogen: organic nitrogen (org-N), ammonium nitrogen, NH_4–N, and nitrite-nitrate ($NO_{2,3}$-N) concentrations in the influent greywater and the effluent from different filter material configurations during the different loading rates. Bottom: Particulate and dissolved fractions of total phosphorus in the influent greywater and the effluent from the different filter material configurations for the different loading rates.

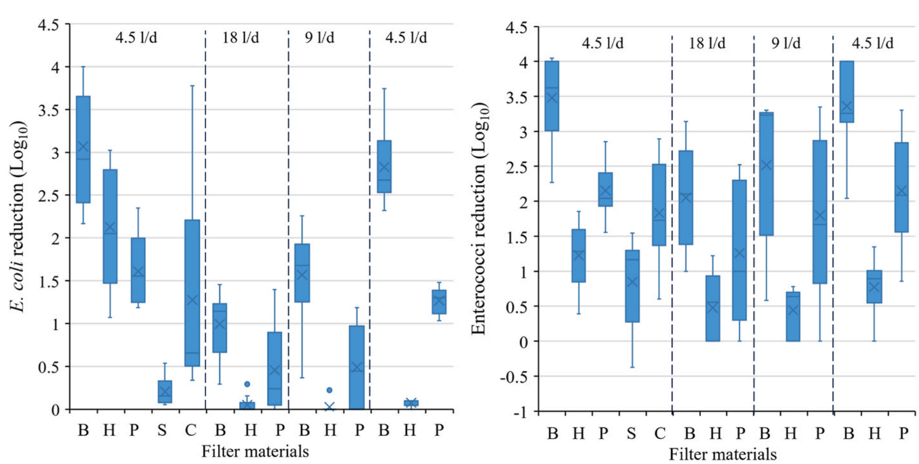

Fig. 7. Reduction of *E. coli* and enterococci by the filter materials (biochar (B), hemp (H), pumice (P), SCG (S), CFS (C)) during different hydraulic loading rates. Data for CFS are shown for the initial 4.5 l/d since that trial had the same 8-week establishment phase as SCG. To calculate the log-reductions, censored data were set to the reporting limit or greater-than value.

M. scorpioides grew and survived longer in the SCG and CFS configurations compared to hemp, pumice, and biochar (Supplementary Material Figs. A3 and A5). Two of the three *M. scorpioides* plants died in the biochar material during the six weeks of greywater irrigation before the first sampling period. Interestingly, after 15 weeks, all the *M. scorpioides* plants had died except the plants in one of the pots with pumice, which survived until the end of the experiment, which was somewhat surprising (Supplementary Material, A4). Assessing the growth of plants, biochar material was relatively less favorable for the plant species.

4. Discussion

4.1. Treatment efficiency of the studied filter materials at different HLRs

The biodegradability of wastewater is indicated by the COD:BOD ratio and a ratio lower than 2 is considered to be suitable for biological treatment processes (Metcalf & Eddy, 2014). The greywater in this study had a COD:BOD ratio ranging between 1.8 and 3.4 with an average of 2.3 which was similar to the ratio of 2.2 reported by Li et al. (2009) and Noutsopoulos et al. (2018). In addition, a ratio of 100:20:1 for COD:N:P was suggested by Metcalf & Eddy (2014) for enhanced biological treatment. However, the greywater in this study was deficient in N resulting in a ratio of 100:3.3:0.4 for COD:N:P. Such low N is expected in greywater as reported by Shaikh and Ahammed (2020). A similar C:N ratio of 100:3.3 was also observed by Dal Ferro et al. (2021) (100:3.3) and Hernández Leal et al. (2011) (100:3.5). In addition, the ratio of BOD:P of the greywater (60/1–148/1) was more than the 30:1 ratio suggested by Metcalf & Eddy (2014) for enhanced biological phosphorus removal. A higher BOD:P ratio increases the availability of readily biodegradable COD for heterotrophic denitrifying bacteria for nitrogen removal and phosphorus accumulating organisms for phosphorus removal. Nevertheless, despite the N deficiency, the overall treatment performance showed that the filter materials were efficient.

Biochar provided the most effective overall treatment under the different hydraulic loading rates, as reflected in the highly efficient BOD reduction by >99%, the removal of 60%–89% TN, 31%–75% TP, and the removal of indicator bacteria (Fig. 7). Similar treatment efficiency was observed by filter materials with biochar additives such as a mix of perlite + coco coir + biochar (Boano et al., 2021) or lava rock + organic soil + biochar (Lakho et al., 2021). The fine biochar particles with high adsorption capacity and the presence of macro and micro-pores in biochar could have enhanced the biological treatment including microorganisms removal as found in previous studies (Dalahmeh et al., 2016; Nguyen et al., 2021). Biochar also removed TN about as effectively as did pumice (mean effluent concentration of 2 mg/l) during the high loading rate of 18 l/d. TP removal increased from week 9 to week 19, amidst the change in loading rates, suggesting that efficacy may be less influenced by the loading rates than by physicochemical processes such as adsorption to the substrate material (Pradhan et al., 2020). Since the vegetation growth was low in biochar configurations (visual observation), the possibility of vegetation uptake of N and P can be eliminated, which was also reasoned in the studies by Fowdar et al. (2017) and Prodanovic et al. (2019a, 2019b). However, the increased influent BOD during the loading rate of 18 and 9 l/d, respectively, resulted in a BOD:P ratio >30/1 which may have increased the availability of a carbon source for biological activities to treat the TN and TP through assimilation into microbial biomass (Dalahmeh et al., 2014; Fowdar et al., 2017). In addition, during the high loading rates, the distribution of greywater in the filter material was probably better, and therefore more particle surface area and pores were available for adsorption and microbial growth.

Pumice was the coarsest of the filter materials tested and is likely to have had the highest infiltration capacity, thus reducing the contact time and potential for adsorption within the filter (Karimaian et al., 2013; Prodanovic et al., 2017). The treatment efficiency of the pumice was much higher compared to LECA and perlite filter material investigated by Masi et al. (2016), Prodanovic et al. (2019a, 2019b), and Pradhan et al. (2020). However, the green wall study with LECA filter material by Zraunig et al. (2019) showed results similar to the ones in the present study. The removal of nutrients by pumice at the high loading rate (18 l/d) was 80% for TN and 86% for TP which was significantly higher than the other loading rates, viz. 4.5 l/d and 9 l/d which removed 48%–54% of TN and 44%–62% of TP. This trend of higher nutrient removal with high loading rates was also observed in the study by Zraunig et al. (2019) using LECA material, while other studies have found low nutrient removal at high loading rates (Prodanovic et al., 2019a; Pradhan et al., 2020). Apart from the high organic load, the probable reason for such conflicting observations could be that during high loading rates, the influent greywater within the filter materials could be more dispersed and so enhance the effective adsorptive area of the pumice present, similar to biochar. Interestingly, during the 18 l/d loading rate, fine particles were released into the effluent as indicated by a high TSS concentration (119 mg/l) (see supporting information), which was significantly higher than during the lower loading rates. However, such washout of particles did not correspond with wash out of N and P in the effluent, which was also observed by Dalahmeh et al. (2014) and Zraunig et al. (2019). Therefore, it remains uncertain whether it is mainly physicochemical or biological processes that underlie the treatment of nutrients in pumice.

Hemp was less efficient than coco coir has reportedly been (Masi et al., 2016; Pradhan et al., 2020; Prodanovic et al., 2017). Its removal of organic matter improved during the experimental period, from sampling campaigns 1 to 4 (both 4.5 l/d), while nutrient removal deteriorated (Fig. 4). However, the hemp was seen to degrade during the experimental period, which may have been the reason for the reduced nutrient removal capacity (Fig. 4). In addition to the high organic load of 18.0 g BOD/m^2/d during the final 4.5 l/loading rate, the degradation of hemp material may also have contributed to dissolved organic carbon. The degraded hemp material resulted in a sludge-like in consistency, and it is possible that anaerobic zones were established in the pot, which could explain the removal of nitrogen, possibly by nitrification–denitrification process as was also observed by Dalahmeh et al. (2014); Prodanovic et al. (2019a, 2019b), observed during weeks 9, 12 and 15 (Fig. 4). In addition, PAOs may have contributed to the enhanced biological phosphorus removal in the hemp configurations. No nitrification occurred in hemp during the final week of the experiment (sampling campaign 4), possibly because of the conditions in the hemp configurations caused by material degradation. Hemp fiber has higher cellulose but lower lignin content (Sadrmanesh and Chen, 2019) than coco coir, which contains much lignin making it tough and very rigid (Ali et al., 2022). These characteristics may well have affected the degradation of hemp under continuous greywater irrigation, and so may have progressively influenced the results. However, fibrous materials like coco coir or textile fibers are prone to clogging the system (Prodanovic et al., 2017; Galvão et al., 2022) but such phenomenon by the hemp material was not observed, even after degradation.

The CFS material was effective in treating greywater in respect of all parameters investigated, especially regarding nutrient removal as reflected in the low effluent concentrations of TN (3.1 mg/l) and TP (0.3 mg/l) (see supporting information). However, some ponding in some pots of the CFS configurations did occur during the sampling campaign after 8 weeks of greywater irrigation. Boano et al. (2021) found that composted material like CFS can lead to clogging of the system. Such ponding and clogging issues of CFS can be problematic at higher loading rates. Therefore, a higher proportion of pumice in the mix could potentially increase the infiltration capacity of CFS and would be worthy of further investigation in future studies. Among the five filter materials investigated, SCG performed the least well, contrary to the findings by Pradhan et al. (2020). The effluent from SCG contained higher concentrations of organic matter and nutrients than the influent (see supporting information). One important reason for its poor performance in this study could be the avoidance (for environmental reasons) of SCG pre-treatment with a formaldehyde solution, as was carried out by Pradhan et al. (2020). Moreover, the SCG material was fine-grained with low hydraulic capacity, which resulted in high retention time; consequently, the SCG configurations started to pond even at the lowest loading rate (4.5 l/d), suggesting it to be unsuitable for higher loading rates.

Surfactants mainly originate from detergents and personal care products, have been found to be biodegradable under aerobic conditions (Khalil and Liu, 2021), and can contribute to 15% of COD (Hernández Leal et al., 2011). Long-term exposure to surfactants in greywater can have a negative effect on soil properties by increasing hydrophobicity (Wiel-Shafran et al., 2006; Hernández Leal et al., 2011). The concentration of surfactants in greywater was reported to be between 0.7 and 70 mg/l (Wiel-Shafran et al., 2006) from six domestic sources while the concentration from 32 residential houses was 41 ± 12 mg/l (Hernández Leal et al., 2011). The concentration of surfactants in the influent greywater used in this study was <1 mg/l which was below the recommended maximum concentration limit in water for irrigation (Hernández Leal et al., 2011).

An increase in HLR affected the removal of microorganisms e.g., *E. coli*, with higher concentrations in the effluent (Table 2). The removal of microorganisms is highly influenced by the characteristics of the filter materials e.g. porosity, straining, adsorption capacity, and biofilm development (Stevik et al., 2004; Qian et al., 2022). As the retention time decrease with the increase in HLR, removal by filter materials like pumice decrease (Stevik et al., 2004; Prodanovic et al., 2017). In addition, the influent concentration of microorganisms can also affect the removal efficiency, with large quantities of microorganisms occupying the adsorption surfaces in the filter materials as observed by Qian et al. (2022). The fine-grained biochar with high porosity showed effective removal of microorganisms at low loading rates but during the higher rates, the effluent concentrations of microorganisms were high. This indicates that for the effective removal of microorganisms, an optimum, stable, and rather low HLR is favorable as suggested by Prodanovic et al. (2017). In addition, higher HLR can lead to the release of retained microorganisms in the effluent which probably was the case in this experiment.

Visual assessment of the effluent quality showed the biochar effluent to be the clearest, which is also supported by the turbidity and TSS data (see supporting information). Effluents from pumice configurations were slightly yellowish in coloration, while effluents from hemp and CFS had a yellowish tint. The effluents from SCG were dark brownish with a certain odor, unlike the other effluents.

4.2. Effect of time on treatment

Despite the 8-week establishment period with tap water and greywater prior to the first sampling event (Fig. 2), it was uncertain if the efficiency of the materials at treating influent greywater would be constant during the experimental run time. The effect of time on the effluent concentrations of organic matter (BOD) and nutrients (N and P) was studied using Wilcoxon signed-rank test, comparing the first and last sampling campaign, both at the loading rate of 4.5 l/d (Fig. 2). For the hemp and biochar configurations, the effluent BOD determined during these two sampling campaigns showed no statistically significant difference. This indicates an effective treatment of the organic matter in the hemp and biochar configurations over time, with stable effluent concentrations that were low even when concentrations in the influent were high (as was the case during sampling campaign 4 when the influent BOD was 333 mg/l, Fig. 4). As the efficacy of removing organic matter did not change over time, the statistical evaluation of the effect of the loading rates on the efficiency of the hemp configurations remained valid. The mean effluent concentrations from the pumice configurations, however, were significantly lower during sampling campaign 4 (BOD of 3 mg/l) compared to sampling campaign 1 (BOD of 5 mg/l, Fig. 4). This significant difference between the initial and final sampling campaign indicates the development of biofilm on the filter material over time and makes it difficult to evaluate the effect of loading rate on the pumice material.

The degradation of the hemp material, as discussed above, probably contributed to this poor removal of TN and TP. The mean effluent concentrations of TN from the biochar configurations reduced from 6.3 mg/l to 3.9 mg/l from the first to the final 4.5 l/d loading rate (Fig. 6). This could be due to the development of a suitable environment for microorganisms and the growth of biofilm within the materials as also observed by other authors (Pradhan et al., 2020; Zraunig et al., 2019). In addition, the high loading rates investigated beforehand (9 l/d and 18 l/d) could have enhanced the flow distribution in the biochar material allowing more aeration. Moreover, the concentration of influent organic material in the final 4.5 l/d was much higher which may have contributed to increased biological activity (Dalahmeh et al., 2014). The removal of TN by pumice between the two 4.5 l/d loading rates did not differ significantly although the mean effluent concentration slightly decreased from the first to the final 4.5 l/d (from 8 to 7.2 mg/l, Fig. 6). However, the TP effluent concentrations from pumice in the final 4.5 l/d were significantly higher (1.1 mg/l) than under any other loading rate investigated. This poor removal might be associated with the leaching of adsorbed P from the previous loading rate periods as observed by Dalahmeh et al. (2014) in charcoal filters. In contrast, the effluent TP concentration (0.5 mg/l) from biochar during the final 4.5 l/d was lower than the initial 4.5 l/d (1.5 mg/l). As biochar was a much finer-grained material than pumice aggregates (Ø 2–8 mm) it provided a slower filtration rate (practical observations), the treatment of P in biochar was therefore possibly biological, with biofilms as observed by Prodanovic et al. (2017) in perlite - coco coir mix or by PAOs as discussed above.

To summarize, the results from the two 4.5 l/d loading rates suggest that the treatment of organic matter by biochar and hemp did not vary significantly with the duration of exposure to greywater, in contrast to the nutrient concentrations in the effluents which showed significant differences in some cases. While improved nutrient treatment was observed in the biochar material due to enhanced biological activities, degradation of the hemp material deteriorated its performance with time. Moreover, the effect of time on the pumice material was small; a slight improvement was observed for BOD and nitrogen. However, the leaching or desorption of nutrients and washout of organics including biofilm could be an issue in the long-term use of materials like biochar or pumice where hemp is unsuitable for long-term use.

4.3. Investigated filter materials

Although the selection of the filter materials was based on previous studies, other aspects were also considered, such as their local availability, natural occurrence, recycled material content, and environmental friendliness. The biochar used in this study was derived from wood-based by-products (hardwood, spruce, shrubs) following pyrolysis at temperatures in the range of 500–700 °C for about 20 min. Biochar was found to have a positive impact on the environment, especially in carbon sequestration (Thompson et al., 2016), enhance the hydraulic properties of the soil structure (Winsley, 2007), and provide effective greywater treatment as the pores provide a large specific surface area (Boano et al., 2021; Dalahmeh et al., 2016). Such effectiveness was observed in this study as well. Pumice is a commonly available material in Sweden as a gardening material. Commercially available pumice of particle size Ø 2–8 mm was purchased and sieved to remove finer particles below Ø 2 mm. It is also used in wastewater treatment due to its good adsorption characteristics (Karimaian et al., 2013) and its positive influence on plant growth (Eksi et al., 2020). In addition, unlike perlite and LECA, pumice is mined and crushed into small pieces and does not need thermal expansion which makes it environmentally friendly. However, the transportation of pumice from where it is mined can have a negative impact on the environment (Öhrn Sagrelius et al., 2022). Hemp is a low-cost plant-based fiber with good sorption properties, mechanical strength, high porosity, and absorbency (Crini and Lichtfouse, 2020) but its use in greywater treatment has not been studied previously. Hemp was therefore chosen as an alternative to coco coir, since although the latter has already been found to provide effective treatment of greywater (Masi et al., 2016; Pradhan et al., 2020; Prodanovic et al., 2017), it is not locally available in Sweden. Spent Coffee Grounds (SCG) have been reported to have physical properties similar to coco coir and sand, being able to remove total nitrogen and ammonium effectively from greywater (Pradhan et al., 2020). SCG used in this study was collected from a local coffee shop, rinsed several times under running tap water, and then oven dried. However, the inefficient treatment of SCG in this study suggests that it needs further pre-treatment like Pradhan et al. (2020) or make biochar from SCG (Oh and Sohn, 2022) . The composted fiber soil (CFS) was made from wood fibers - a by-product of the pulp industry in northern Sweden. Such composted materials have been found to provide effective treatment (Boano et al., 2021; Eksi et al., 2020). Since biochar and CFS have shown promising results, future studies should focus on their different mix proportion with pumice to find optimum treatment efficiency.

4.4. Resilience of plant species

The plant species selected for this study were not resilient to greywater irrigation, as assessed by their growth and survival. The plants chosen were outdoor plants that like wet conditions, but the green wall was set up indoors, which could have affected their growth. It was also observed that the plants in the lower pots (second and third rows) flourished rather better than the upper pots (Supplementary Material, Figure A2–A5) in contrast to the observations of Prodanovic et al. (2020). This indicates that the raw greywater and its pollutant concentration might have affected the plants in the upper pots more than the lower. *M. scorpioides* was the least resilient plant species; although it survived well during the initial three weeks of tap water irrigation (Fig. 2), its growth deteriorated after six weeks of greywater irrigation during the establishment phase (Supplementary Material, Figures A3). In contrast, *C. nigra* and *J. compressus* grew well until the end of the experiment; these species may therefore be suitable for green walls treating greywater. However, since sodium and chloride are toxic to vegetation (Khajvand et al., 2022; Siggins et al., 2016), plant growth in the green wall might have been affected by the concentrations of these ions in the greywater.

4.5. Practical considerations

The time of the establishment of the filter material to achieve effective treatment is important when a green wall is intended for full-scale treatment in an outdoor setup. However, organic materials like hemp, which degrade over time, should be used carefully as this seriously affects treatment efficiency. Some materials like SCG and CFS are prone to ponding in small pots as used in our experimental set-up, especially under higher loading rates. This can lead to overflow, contamination of surroundings, and reduced treatment performance. A proper irrigation system is essential to provide an even distribution of greywater and to optimize the use of the available surface area of the filter. In addition to the HLR, an intermittent dosing regime can influence the treatment by allowing oxygen diffusion in the filter materials for the biological oxidation of the adsorbed organic matter. Moreover, setting up a such green wall in public places can become a health hazard due to the risk of pathogens not being effectively removed especially during high loading rates. A disinfection step is recommended if the effluent is intended for reuse.

The *Gro-wall® 4.5* module used was a well-made rigid structure; however, water losses along the structure occurred during the experiment rendering it unsuitable for full-scale greywater treatment. In addition, insects (e.g., flies) and other invertebrates (e.g., small slugs) were observed around the module structure (some of which were breeding in the filter material), making the green wall environmentally and aesthetically unpleasant in an urban setting.

Concerning the hemp material in particular, apart from biodegradation of the material itself, small flies, slugs, and larvae were found to be living and developing in the pots. These organisms might have originated from the material itself but more likely, they were carried with the greywater. Larvae were also observed in the effluent. During the initial stages of the experiment, fungi (i.e., mushrooms) were observed to grow in some of the pots filled with hemp material. Flies and larvae were also visible in the SCG pots, but less so in the pots filled with pumice or biochar. Moreover, when emptying the pots of CFS configurations after the end of the experiment, earthworms were observed to be present, which were probably in the material when purchased and might have originated from the composting process.

5. Conclusions

Green walls have the potential to be developed as a decentralized system for greywater treatment when used with suitable filter materials as substrates for plants. Three of the five materials investigated in this study – biochar, pumice, and composted fiber soil (CFS) - showed promising results in the efficient treatment of greywater regarding the removal of organic matter (biological oxygen demand (BOD)) and nutrients (total nitrogen (TN) and total phosphorus (TP). The hydraulic loading rates had a significant negative influence on hemp and pumice but not on biochar as the effluent concentrations of organic matter increased with increasing loading rates. However, efficient BOD reduction under the different loading rates of 4.5 l/d, 9 l/d, and 18 l/d was achieved by hemp (82%–94%), pumice (93%–99%), and biochar (>99%). Pumice and biochar removed organic matter more efficiently than hemp under all loading rates tested; biochar consistently performed most efficiently at reducing chemical oxygen demand (COD) and total organic carbon (TOC) by >95%. However, during the high loading rate (18 l/d), pumice had the highest removal efficiency of TN (80%) and TP (86%) with effluent concentrations of 3.4 mg/l and 0.3 mg/l, respectively. TP removal by biochar improved from 31% to 75% during the whole experimental period where effluent TP concentrations reduced from 1.5 mg/l to 0.5 mg/l. The CFS reduced BOD by 99% and reduced TN by 82% and TP by 85% with effluent concentrations of 3 mg/l, 3.1 mg/l, and 0.3 mg/l, respectively (at 4.5 l/d loading rate). Spent coffee grounds (SCG) were the least efficient material, releasing more organic matter and total nitrogen (TN) into the effluent than was present in the influent. The concentration of surfactants in the influent was <1 mg/l during the whole experimental period, more than 90% of which was removed by biochar and pumice. The influent *E. coli* and enterococci concentrations were >100,000 cfu/100 ml in many cases. Biochar was the most efficient material in removing indicator bacteria, especially during low loading rates, with 2.2–4.0 Log_{10} reduction for *E. coli* and enterococci. When comparing the two 4.5 l/d loading rates (10 weeks apart), biochar showed significant improvement in the removal of nutrients, while for pumice improvement in reducing BOD was observed, but biodegradation of hemp led to poor removal of nutrients. Visual observations revealed that the resilience of the plants depended on the pollutant load of the greywater, position in the green wall, and the type of substrate. The effective treatment of greywater can therefore be achieved using a green wall when provided with suitable filter materials and hydraulic loading rates. However, the effluent concentrations of bacteria were still high (>100,000 cfu/100 ml E. *coli*), which indicates that the green wall needs to be designed in such a way to avoid anybody coming into contact with the effluent water; this might be achieved by directly infiltrating the effluent into the ground or adding disinfection step.

Contribution of authors

Mashreki Sami: Conceptualization, Methodology, Investigation, Data Curation, Formal analysis, Visualization, Writing – Original Draft. **Annelie Hedström:** Conceptualization, Methodology, Visualization, Supervision, Writing – Review & Editing, Funding acquisition. **Elisabeth Kvarnström:** Conceptualization, Supervision, Writing – Review & Editing, Funding acquisition. **David T. McCarthy:** Conceptualization and Writing – Review & Editing. **Inga Herrmann**: Conceptualization, Methodology, Investigation, Supervision, Writing – Review & Editing, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.117998.

Supporting information

The raw dataset of this study can be found on the Swedish National Data (SND) Service's website at https://doi.org/10.5878/h5w8-ak85.

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