



Performance of a green wall in treating organics, nutrients and pathogens in greywater in a cool climate

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ABSTRACT

This study investigated the performance of the vertECO® green wall system with lightweight expanded clay aggregate (LECA) and biochar-pumice media in treating greywater from an urban city district (1000 residents) under Scandinavian climate conditions. Over one year, the system effectively removed organic matter, achieving 90–97 % of biological oxygen demand (BOD) reduction and 56–94 % for total suspended solids (TSS). However, nitrogen and phosphorus removal were inconsistent and low. Significant reductions of up to 5.1 Log₁₀ of *Escherichia coli* (*E. coli*), 4.0 Log₁₀ of enterococci, 4.5 Log₁₀ of *Pseudomonas aeruginosa*, and 2.7 Log₁₀ of *Clostridium perfringens* were observed, while *Legionella* and *Campylobacter* were not detected. Cold temperatures (<5 °C) and vegetation had a minimal impact on the treatment performance. Among 17 plant species, *Carex nigra*, *Armeria maritima*, *Lythrum salicaria*, and *Menyanthes trifoliata*, *Comarum palustre*, *Caltha palustris*, and *Iris sibirica* showed high resilience. Despite the effective treatment of organic matter and pathogenic microorganisms, the average effluent quality did not meet the European Commission's Class A requirement (≤10 mg/L for BOD and TSS, ≤5 NTU for turbidity, and ≤10 CFU/100 mL for *E. coli*) for the reuse of reclaimed water in agriculture. Moreover, the microbial quality of the effluent indicated the necessity of a hygienisation step and protective measures to reduce infection risks if such a green wall system is placed in a public setting.

1. Introduction

Wastewater treatment and resource recovery are important practices for sustainable environmental management, focusing on combating eutrophication, water scarcity, and global climate change. Domestic wastewater can be divided into two fractional categories based on the source of generation: blackwater from the toilet, and greywater originating from the kitchen sink, dishwasher, hand basin, shower, and laundry. With a growing implementation of source separation technology for wastewater, blackwater, and greywater are collected and treated separately. In addition, decentralized greywater treatment systems can be economical considering the potential of water and heat recovery, and reduced energy demand [1,2]. Shaikh and Ahammed [3] reported that greywater generation varies from 14 to 140 L/p/d in low-income countries to 62–223 L/p/d in high-income countries. The average water consumption in Sweden, for example, was reported to be 136 L/p/d

in 2018 [4]. Based on this, and considering that 70 % of domestic wastewater is greywater [3], the average greywater flow is 95 L/p/d. Therefore, treatment and reuse of greywater could contribute significantly towards the integrated water resource management to tackle the growing challenges of water scarcity and to the Water-Energy-Food NEXUS [5].

Typically, greywater contains organic matter, nutrients, microorganisms, metals, and hazardous substances such as micropollutants, including pharmaceuticals [6–8]. The quality of greywater varies with the source of generation, i.e., the kitchen, hand basin, shower, and/or laundry. The organic matter, commonly measured as Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), in greywater from kitchens and laundry was reported to be approximately 2 to 5 times higher than in other sources, such as showers or hand basins [3,7]. The nitrogen and phosphorus in greywater come from food residues and personal care products. The concentration of phosphorus in

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greywater has decreased in recent years due to the increasing use of phosphorus-free detergents [9,10]. However, treatment is necessary to meet local discharge limits, such as 3 mg/L (or 1 mg/L in case of sensitive water bodies) for on-site mixed wastewater treatment systems [11], while wastewater treatment plants in Sweden are subject to even stricter discharge limits [12].

Additionally, greywater contains pathogenic microorganisms such as bacteria, protozoa, and viruses that originate from fecal contamination during showering or laundry (e.g., washing undergarments and diapers). The washing of raw food items (e.g., meat, vegetables, and fruits) can also contribute pathogenic microorganisms to greywater from kitchens [13]. The presence of *E. coli*, enterococci, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Legionella* spp., *Salmonella* spp., *Campylobacter*, *Clostridia*, *Cryptosporidium*, *Giardia*, noroviruses, enteroviruses, and rotaviruses was reported for both raw and treated greywater [13,14]. Therefore, the presence of pathogenic microorganisms can pose a public health hazard if not treated properly with disinfection [15].

Greywater treatment using nature-based solutions (NBS) such as green walls is gaining in popularity [16]. Green walls, also referred to as living walls or vertical wetlands, integrate substrate-based filtration, biological degradation, and plant-root zone processes to facilitate greywater treatment [9,16]. There are only a few studies on green walls using real greywater, i.e., generated from residential buildings, areas, or student dormitories [17–22]. In addition, seasonal temperature is a critical environmental parameter in nature-based treatment systems, with several studies reporting improved treatment performance at higher temperatures due to enhanced microbial activity [9,20,23]. The Scandinavian climate, with prolonged cold periods and frequent freezing, can affect biological activity, hydraulic performance and vegetation growth in nature-based treatment systems. Therefore, evaluating the green wall under these conditions is essential to assess its resilience and treatment efficiency.

The aim of this study was to evaluate the treatment performance of a green wall system in removing organic matter, nutrients, and pathogenic microorganisms from greywater under Scandinavian climate conditions. In addition, the study assessed the resilience of selected vegetation species to long-term greywater exposure.

2. Methods and materials

2.1. Green wall setup

An experimental green wall was set up and studied at RecoLab, a testbed facility, situated in Helsingborg, Sweden. RecoLab is connected to a nearby urban city district, which generates source-separated greywater (1000 residents approximately at the time of the study) from five residential buildings, an office building, two restaurants, two beauty parlors, a school, and a hotel [12]. For the green wall setup, the verTECO® green wall system was used (Fig. 1), which was developed by alchemia-nova and refined during the EU H2020-funded HOUSEFUL project (grant agreement number 776708). The modular system consisted of four levels (LV), LV1–LV4, of stainless-steel containers (500 L each, Fig. 1). The total dimensions of the setup were 2.5 m × 1.5 m × 2.5 m (length, width, and height). In the verTECO® module, the influent was fed from LV1 and flowed horizontally sub-surface through the filter media before overflowing into the subsequent level below, through a height-adjustable outlet pipe (Fig. 1). The final effluent was collected from the outlet of the LV4 (Fig. 1).

Each level of the system was packed with approximately 375 L of substrate (42 cm deep) (Fig. 1), resulting in a total substrate volume of 1500 L. The depth of saturation in each level was set to 36 cm by adjusting the outlet pipe (Fig. 1). Due to practical challenges, October 2023 was the only exception when the influent was fed vertically along the LV1, allowing a trickling flow at that level by lowering the outlet pipe to 10 cm (only for LV1) (Fig. 2). In addition, an air pump (Thomas Denver Gardner LP-200 HN Diaphragm compressor, capacity: 200 L/min) was installed to provide aeration through the perforated tubes at the bottom of each level (Fig. 1) to enhance the aerobic treatment. However, during the establishment phase (Fig. 2), the aeration system failed, presumably due to the blockage of the perforated tubes. This aeration failure was confirmed using OXYBase® WR-RS232-SW dissolved oxygen sensors placed in each level, detecting no oxygen in the filter media.

2.2. Filter media

The substrate used in this experiment was a mix of pumice and biochar in the weight ratio of 1:2, which had been shown to provide effective treatment in a previous study [21]. The biochar used in this

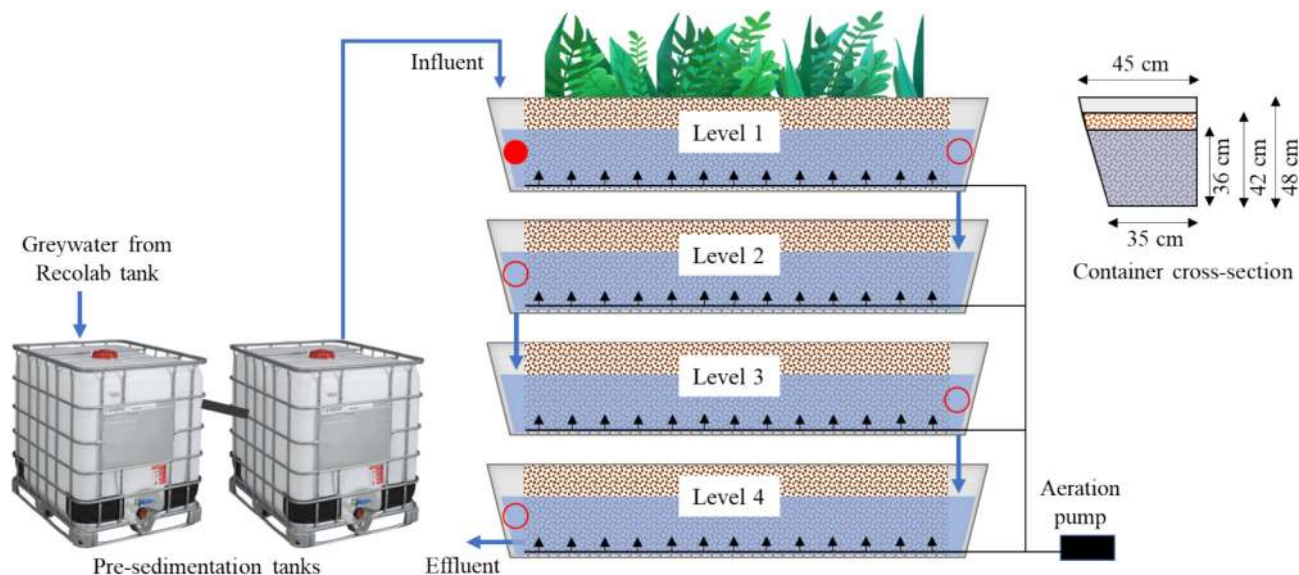


Fig. 1. The schematic of the verTECO® system with the aeration pump and the pre-sedimentation tanks. The sampling point for the influent greywater is marked with the solid dot at Level 1 and the effluent sampling points are marked with circles at the outlet of the Levels 1–4.

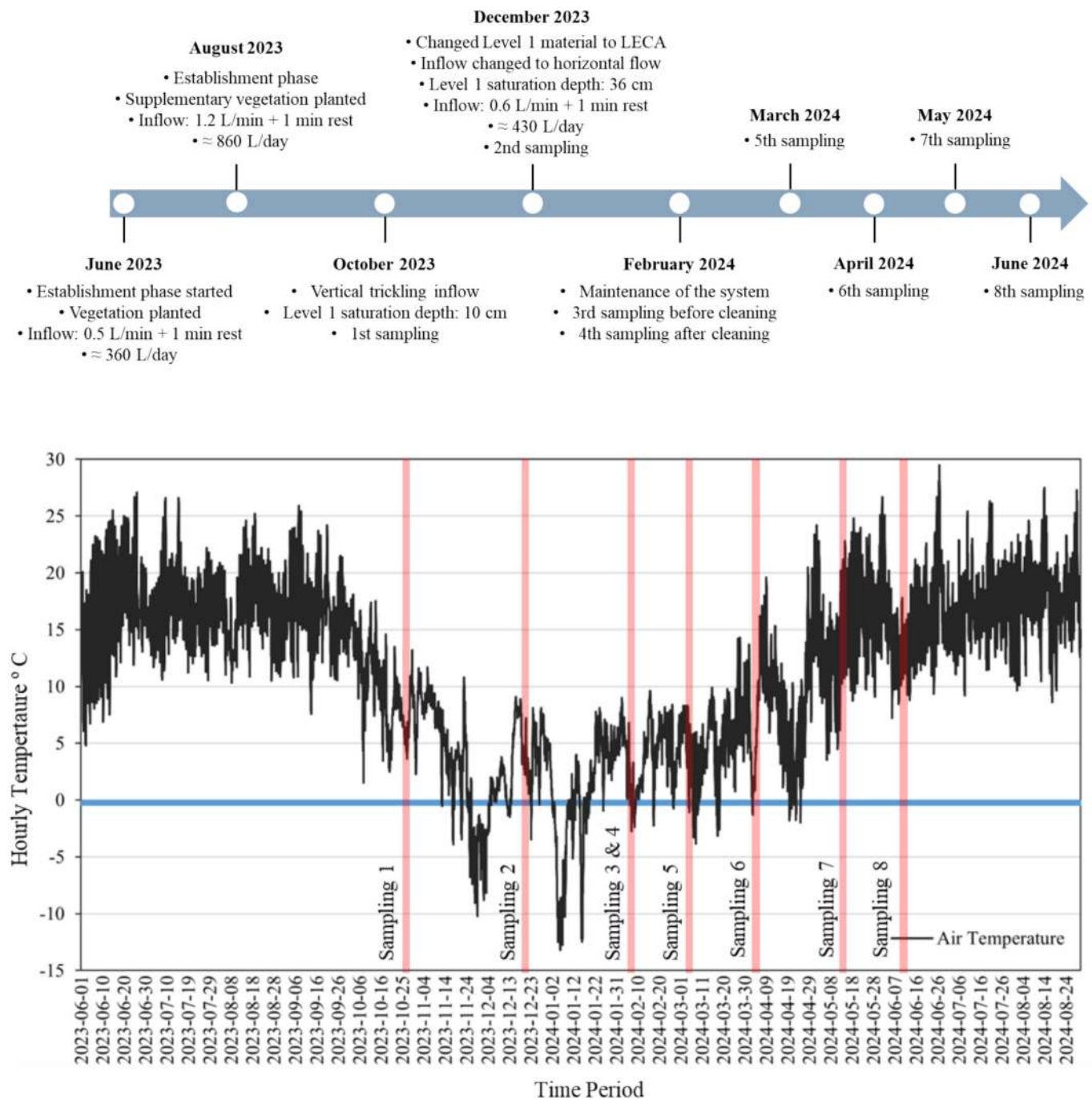


Fig. 2. Timeline showing the changes made in the green wall, flow rates, and sampling campaigns (above) and the seasonal variations of air temperature obtained from the Swedish Meteorological and Hydrological Institute's nearest weather station from the study site (below). The pink vertical lines indicate the sampling events. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

study was produced by the water utility of the city of Stockholm (SVOA), through pyrolysis of wood-based by-products (hardwood, spruce, shrubs) at temperatures in the range of 500–700 °C for about 20 min. Commercially available pumice (Ø 2–8 mm) was used in the mix. In December 2023, the filter media in LV1 were replaced with lightweight expanded clay aggregate (LECA) of size Ø 8–16 mm (Fig. 2) to increase the hydraulic conductivity and reduce the challenges with clogging and ponding. The particle size distribution of the biochar–pumice mix, obtained using a RO-TAP® sieve shaker, was characterized by D10 = 0.06 mm, D50 = 2.49 mm, and D90 = 3.18 mm.

2.3. Pre-treatment

Greywater from the collection tank of the RecoLab greywater treatment plant was pumped into intermediate bulk container (IBC) tanks (1 m³) for pre-sedimentation (Fig. 1). Greywater from the first IBC tank passed into the second by a tube placed at 30 % of the total depth (or 70 cm from the bottom of the tank). The greywater levels were controlled by a level switch placed in the first IBC tank at 90 cm from the bottom. In the second IBC tank, a submersible pump (Biltema DP 402, suction height: 7 m, flow rate 9 m³/h) to feed the green wall was placed at 20 cm below the greywater surface to avoid the scum layer.

2.4. Flow rates and dosing regime

Greywater was pumped from the second pre-sedimentation tank into LV1 of the green wall, as shown in Fig. 1. The green wall was fed continuously throughout the experimental period where the inflow was controlled with a valve and calibrated to the desired flow rate (L/min) with 1 min resting between the inflows (Fig. 2). The different flow rates and dosing regimens during the different phases of the experiment are presented in Fig. 2. At the beginning of the experiment with the vertical trickling flow setup in LV1, with a total surface area of 101.3 m² and the flow rate of 860 L/d was used, corresponding to a hydraulic loading rate of 850 L/m²/d and a volumetric loading rate of 0.57 bed volume/d (BV/d). From December 2023, due to the challenges with clogging and ponding, the inflow was changed to a horizontal flow setup with a reduced and stable rate of 430 L/d. As a result, the hydraulic loading rate was 2530 L/m²/d, based on the cross-sectional area (0.17 m²) shown in Fig. 1, and volumetric loading rate 0.28 BV/d.

2.5. Vegetation

Initially, in June 2023, the green wall was vegetated with twelve different plant species, some of which were suggested in previous literature, and some were based on recommendations from the local nursery. The selection criteria included: i) tolerance to wetland conditions or wetland species, ii) root and leaf growth, iii) tolerance to salinity, iv) aesthetic, flowering, and grassy, and v) suitable in the Scandinavian climate. Initially, the green wall was planted with *Iris sibirica*, *Caltha palustris*, *Zantedeschia aethiopica*, *Ipomoea batatas*, *Hedera Helix*, *Armeria maritima*, *Carex appressa*, *Heuchera villosa*, *Pontederia cordata*, *Schizostylis coccinea*, *Aster macrophyllus*, and *Alchemilla vulgaris*. However, during the establishment phase in August 2023 (Fig. 2), the last five species died and were replaced by *Carex nigra*, *Lythrum salicaria*, *Menyanthes trifoliata*, *Comarum palustre*, and *Eriophorum angustifolium*. Each level of the green wall was planted with one pot-sized plant of each species, and before plantation, the extra soil was washed off, exposing the roots of each plant. The plants were randomly placed 20 cm apart from each other. However, LV1 was not vegetated after the change of filter media in December 2023 (Fig. 2). The resilience and the survivability of the vegetation species were visually assessed, which included regular photographs of the plants, monitoring growth (plant aging/dying), leaf colour status (greening/browning), flowering, and propagation.

2.6. Sampling and analyses

To investigate the effect of seasonal change on the treatment performance of the green wall, samples were taken in the colder and warmer months from October 2023 to June 2024 (Fig. 2). A total of eight sampling events were carried out (Fig. 2), using the Isco 6712 automatic samplers, with which one 24-h composite sample of influent and effluent per sampling event was collected from the respective sampling points shown in Fig. 1. The samples were thoroughly mixed before being transferred into sampling bottles for analysis. However, the samples for microbial quality were taken manually (grab samples) and sent for analysis within 24 h. As the operation of the green wall system was paused during the freezing period (Dec-23–Jan-24), two consecutive samples were taken in February: pre- and post-maintenance of the system (Fig. 2). During the maintenance, greywater in the pre-sedimentation tanks and the green wall levels were drained out (to completely defrost the filter) and refilled before taking the 4th sample.

The samples were analyzed with respect to biochemical oxygen demand (BOD), chemical oxygen demand (COD), total and dissolved organic carbon (TOC and DOC), total suspended solids (TSS), total nitrogen (tot-N), ammonium (NH₄-N), nitrite-nitrate (NO_{2,3}-N), total phosphorus (tot-P) and dissolved phosphorus, and salinity (sodium and chloride). For the dissolved fractions of organic carbon and phosphorus,

samples were filtered through 0.45 µm filters. Analyses of the above-mentioned quality parameters were conducted by an accredited laboratory, ALS Scandinavia AB. In addition, the pathogenic microorganisms *E. coli*, enterococci, *Clostridium perfringens*, *Legionella* spp, *Pseudomonas aeruginosa*, and *Campylobacter* were analyzed in four sampling campaigns (March, April, May, and June of 2024). However, two influent greywater samples could not be analyzed for *Campylobacter* due to high levels of particulate matter (e.g., TSS), and following consecutive non-detects in March and April of 2024, further analysis of *Campylobacter* was discontinued. The microbial analyses were carried out by the Swedish Veterinary Agency (SVA). The analytical standards can be found in the supporting information. For the on-site measurements, a WTW pH 3110 meter paired with a SenTix®41 electrode was used to measure the pH, a WTW Cond 3110 meter and a TetraCon®325 electrode were used for conductivity (µS/cm), and turbidity (FNU) was measured using a Hach 2100Qis turbidimeter.

2.7. Statistical analysis

The effluent quality data from each level were not normally distributed (Shapiro-Wilk test), compromising the assumptions and the validity of parametric statistical tests. Therefore, to compare the treatment at the different levels, the Kruskal-Wallis H test was performed with the Bonferroni correction for multiple pairwise comparison post-hoc test. The statistical analysis was performed using the IBM SPSS software (version 28.0) with a level of significance of 5 %.

3. Results and discussion

3.1. Treatment of organic matter

The treatment of organic matter by the green wall was, in general, effective, as indicated by the removal of BOD and TOC (Fig. 1). The mean influent concentration of BOD was 200 ± 47.9 mg/L, which was effectively reduced by 90–97 % at the outlet of the green wall (LV4) in most cases, except in February 2024, when only an 80 % reduction was achieved prior to the maintenance after the freezing period (Fig. 3). Most of the BOD (80–95 %) was reduced by the levels LV1–LV3, where LV1 with LECA material alone achieved 40–70 % of the BOD reduction. The replacement of biochar-pumice mix media with LECA in LV1 noticeably improved the hydraulic conductivity and reduced clogging and ponding, but affected the removal efficiency of LV1, e.g., the BOD reduction in LV1 decreased from 72 % in October 2023 to 47 % in February 2024. However, the removal efficiency in LV1 gradually improved, ranging between 54 % and 70 % (March–June 2024), which could be associated with the development of biofilms and enhanced microbial activities [9,20]. The final effluent concentrations of BOD from LV4 ranged between 4.0 and 46.4 mg/L during the different sampling events, with the highest being in February 2024, before maintenance (Fig. 3). The influent TOC concentrations were between 34.4 and 111 mg/L, and the mean effluent concentration from LV4 was 11.3 mg/L, mostly in the form of dissolved organic carbon (Fig. 3). The LV1 and LV2 combined removed 65–89 % of TOC (except for the February samples, <40 %). The overall mean influent COD was 423 ± 87.9 mg/L (Table 1) and a similar treatment efficiency of 88 % (mean) was observed. The defrosting and complete draining of the levels during the maintenance may have increased the surface-contact area of the filter media and improved the overall removal efficiency. These overall treatment efficiencies closely align with the previous studies using similar green wall setups such as the vertECO® system for treating greywater [20,22]. However, unlike Zraunig et al. [22], the results showed that changes in seasonal temperature (i.e., colder and warmer months) had a low influence on the treatment efficiency of the green wall with regard to organic matter (Fig. 3).

The treatment efficiency for organic matter in LV4 was significantly lower (Kruskal-Wallis H test) compared to LV1 and LV2 but was very

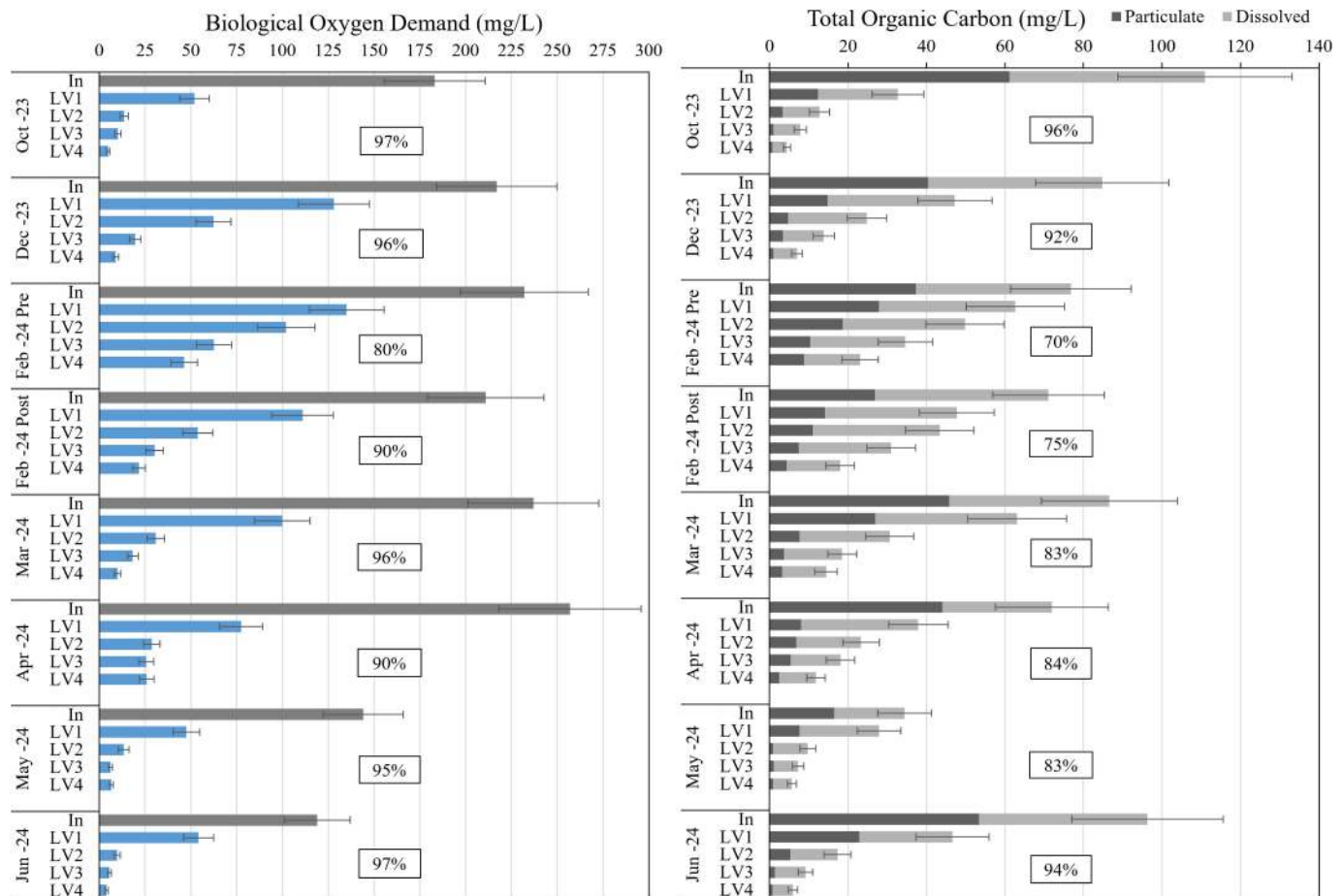


Fig. 3. Concentrations of BOD and TOC measured in the influent (In) and effluent of the four levels (LV1–4) of the green wall with total removal (%) after LV4. Error bars represent analytical uncertainties. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

similar to LV3 (Fig. 3). For biological treatment, a carbon source is important for microbial respiration and activities. According to Metcalf & Eddy et al. [24], a BOD/COD ratio greater than 0.5 typically indicates favorable conditions for enhanced biological treatment. In this study, the influent greywater had a BOD/COD ratio of 0.47 ± 0.54 , which is slightly below that threshold. While this aligns with the 0.45 ± 0.13 reported by Hernández Leal et al. [25] as indicative of aerobic biodegradability, the relatively low average ratio suggests a limited proportion of readily biodegradable organic matter, potentially making biological treatment more challenging. The influent greywater COD: N: P ratio was 100: 2.9: 0.5, indicating the deficiency of nitrogen needed for aerobic treatment but not for anaerobic treatment [25]. The ratio of COD: N decreased gradually from LV1 (100: 5.2) to LV4 (100: 20) including the BOD/COD ratio which decreased to <0.38 . Therefore, the removal of organic matter in the influent greywater by the subsequent levels (LV1–LV3) possibly resulted in low microbial activity, including biofilm growth in LV4. It has been reported that vertical flow treatment systems, including green walls, have higher removal of BOD compared to horizontal flow systems, due to the enhanced oxygenation [9,16], which also aligns with the results of the previous green wall study [21]. In another study, higher treatment efficiency of a vertical flow reed bed was observed when compared with a horizontal flow reed bed [23]. Nevertheless, the BOD removal by the green wall was within the Swedish requirement of 80 % removal for on-site greywater systems [11]. In addition, considering the effluent BOD, LV4 had <10 mg/L (except for the February and April samples) (Fig. 3), which meets the BOD discharge limit of the Öresundsverket wastewater treatment plant, of which RecoLab is a part. In a few cases, the effluent BOD of LV3 was below 10 mg/L, suggesting that a three-level green wall system may be

sufficient for greywater treatment. However, to ensure consistent performance across seasons and loading conditions, the use of all four levels is recommended.

3.2. Nutrient removal

The treatment of nitrogen varied between the levels of the green wall and also across the different sampling months (Fig. 4). The removal of tot-N in the green wall ranged from 16 % to 60 % between the sampling events, except for October 2023 (–14 %) and May 24 (–41 %) when LV4 effluent had higher tot-N concentrations than the influent (Fig. 4). The overall tot-N removal efficiencies were lower than those observed in previous studies using similar green wall systems [20,22]. The low tot-N removal could be due to the failure of the aeration system. During certain sampling events, treatment was ineffective at all levels, with effluent tot-N concentrations exceeding those of the influent, which averaged 12.1 ± 1.8 mg/L (range: 9.6–15.2 mg/L) (Fig. 4). This mean influent tot-N concentration was relatively lower than the previously reported 15.4 ± 8.7 mg/L of tot-N from the RecoLab facility [12] or 26.3 mg/L tot-N in greywater from 32 residential buildings [25]. The average effluent tot-N concentrations across the different levels did not show significant variation between sampling events (Kruskal-Wallis H test). The treatment of ammonium nitrogen ($\text{NH}_4\text{-N}$) by the green wall was low, whereas LV2–LV4 showed significant (Kruskal-Wallis H test) removal of organic nitrogen (org-N) compared to LV1 (Fig. 4). The transformation of org-N to $\text{NH}_4\text{-N}$ in the effluent samples from April, May, and June of 2024 was relatively higher than the other samples from October 2023 to March 2024 (Fig. 4). This higher transformation of org-N could be due to higher seasonal temperature 10–15 °C in

Table 1

The concentration of physicochemical parameters in the influents (In) and the effluents from the different levels (LV1–4) of the green wall during the different sampling campaigns (Oct 2023–Jun 2024).

		Oct	Dec	Feb	Feb	Mar	April	May	Jun
pH	In	7.2	7.2	7.1	7.3	7.1	7.4	7.2	7.3
	LV1	7.0	7.4	7.1	7.3	7.2	7.2	6.9	6.9
	LV2	7.4	7.3	7.2	7.3	7.3	7.3	7.1	7.2
	LV3	7.8	7.4	7.5	7.5	7.5	7.5	7.4	7.5
	LV4	8.0	7.3	7.4	7.5	7.5	7.6	7.5	7.5
Conductivity $\mu\text{S}/\text{cm}$	In	551	541	580	572	576	597	582	679
	LV1	590	581	575	570	621	604	622	745
	LV2	606	629	630	617	685	663	667	760
	LV3	630	631	661	644	671	675	702	756
	LV4	671	620	666	660	664	682	728	756
Turbidity mg/L	In	137	190	173	172	163	286	120	142
	LV1	23.0	106	104	85.6	48.2	36.0	62.0	71.5
	LV2	11.6	40.7	37.5	34.6	19.1	29.0	12.0	12.4
	LV3	7.2	14.0	22.6	12.2	5.7	5.0	7.1	7.3
	LV4	4.4	14.0	21.5	13.7	7.9	6.1	6.9	5.0
TSS mg/L	In	60	68	74	91	130	190	100	93
	LV1	19	42	29	31	14	18	20	36
	LV2	15	18	19	11	8.4	8	6.7	7.8
	LV3	7.5	30	13	6.9	9.1	7.3	14	7.5
	LV4	3.9	30	14	28	27	18	22	15
Sodium mg/L	In	76.5	80.3	80.8	76.9	77.1	75.6	73.9	77.8
	LV1	75.1	83.7	80.4	69.8	77.3	74.1	74.2	77.9
	LV2	72.8	81.1	78.4	68.8	73.7	78.8	76.7	82.2
	LV3	75.7	75.6	77.9	71	75.4	77	76.9	84.3
	LV4	79.7	71.2	76.8	72.1	74.6	78.5	79.2	83.8
Chloride mg/L	In	59.4	65.8	69.9	80.9	67.5	71.9	65.0	65.5
	LV1	59.8	67.2	68.9	69.1	67.2	66.5	64.5	68.8
	LV2	59.9	66.8	69.9	68.2	65.1	67.4	65.0	66.9
	LV3	60.5	65.6	69.4	69.1	63.1	69.1	65.3	66.2
	LV4	57.2	65.1	69.4	69.7	63.3	68.6	66.7	69.6
COD mg/L	In	369	438	522	441	423	559	322	313
	LV1	123	297	371	317	223	191	167	177
	LV2	43.9	168	231	198	118	96.1	61.4	46.5
	LV3	31.5	56.8	183	144	80	83.9	44.2	28.4
	LV4	13.5	30.5	117	94.2	56.9	37.9	28.3	16.8

April–June 2024 (Fig. 2), which accelerates the rate of ammonification [26]. In addition, nitrification of $\text{NH}_4\text{-N}$ was low, which could be explained by the absence of oxygen in the system [22,26], resulting in a very low nitrite-nitrate ($\text{NO}_{2,3}\text{-N}$) concentration ($<0.4 \text{ mg}/\text{L}$) in the effluents (Fig. 4). Furthermore, the reduction of readily available carbon source in the upper levels (e.g., LV1) (Fig. 3) could further prevent overall microbial activity necessary for nitrogen removal [26]. In a previous green wall study, which was a vertical flow system with intermittent loading and unsaturated conditions, almost complete nitrification by the biochar-pumice media was observed [21], indicating the importance of aerated conditions. In addition, the results indicated that plant uptake did not influence the treatment of nitrogen (Fig. 4). Therefore, the removal of nitrogen achieved was associated primarily with mechanical filtration of the organic fraction.

The capacity of the green wall to remove dissolved phosphorus was already exhausted after the first sampling in October 2023 (Fig. 4), when P concentrations were lower in the effluent than in the influent. The overall influent tot-P concentration ranged between 1.7 and 2.8 mg/L with a mean of $2.1 \pm 0.3 \text{ mg}/\text{L}$. Except for the sampling event in October 2023, all the effluent tot-P were above 1 mg/L , which is the discharge limit for on-site mixed wastewater treatment systems in sensitive areas in Sweden [11]. A previous study using the vertECO® system also observed low treatment of phosphorus, indicated by the phosphate concentration may be due to the low influent phosphate concentration ($<1 \text{ mg}/\text{L}$) [22]. The highest removal of tot-P, 79 %, was observed in October 2023 when LV1 had biochar-pumice mix media (Fig. 4). The tot-P removal efficiencies were lower than the $>87 \%$ total phosphate observed by Ramprasad et al. [20] using a similar treatment system with sand, brick aggregates, and gravel as filter media. The results also showed increased particulate phosphorus in the effluent from LV4 (except for October 2023) (Fig. 4), which is in accordance with the

higher TSS from LV4 mentioned in the previous section. In addition, filter media (i.e., LECA and biochar-pumice mix) can release previously adsorbed phosphorus [22] and influence the final effluent tot-P concentration and resulting in low removal efficiencies (Fig. 4).

3.3. Physicochemical parameters

The physicochemical environment of the green wall remained stable throughout the study period, characterized by a well-buffered and consistent treatment process. The values for pH showed a slight increase from the influent greywater entering LV1 (approximately 7.2) to the effluent from LV4 (approximately 7.5), reflecting the stable conditions within the filter media. Conductivity and salinity (Na and Cl) were relatively constant between the influent greywater and the effluents from the LV1–LV4 levels (Table 1), indicating minimal chemical or biological interaction with the filter media [27]. However, an increase in conductivity and Na was observed in the June effluents (Table 1), likely linked to increased evapotranspiration during the warmer month [28,29].

Mechanical filtration within the filter media resulted in high removal of particulate matter. The influent TSS concentration ranged between 60 and 190 mg/L , however, the concentrations from LV4 were consistently higher than LV1, LV2, and LV3 (Table 1). The mean effluent TSS from LV4 was $19.7 \pm 8.8 \text{ mg}/\text{L}$, significantly higher (Kruskal-Wallis H test) than LV3's $11.9 \pm 7.8 \text{ mg}/\text{L}$ (Table 1). Despite this variation, TSS removal at LV4 remained high, ranging between 55 and 94 %. Turbidity followed a similar trend to TSS, showing significant reduction across the treatment levels (Table 1).

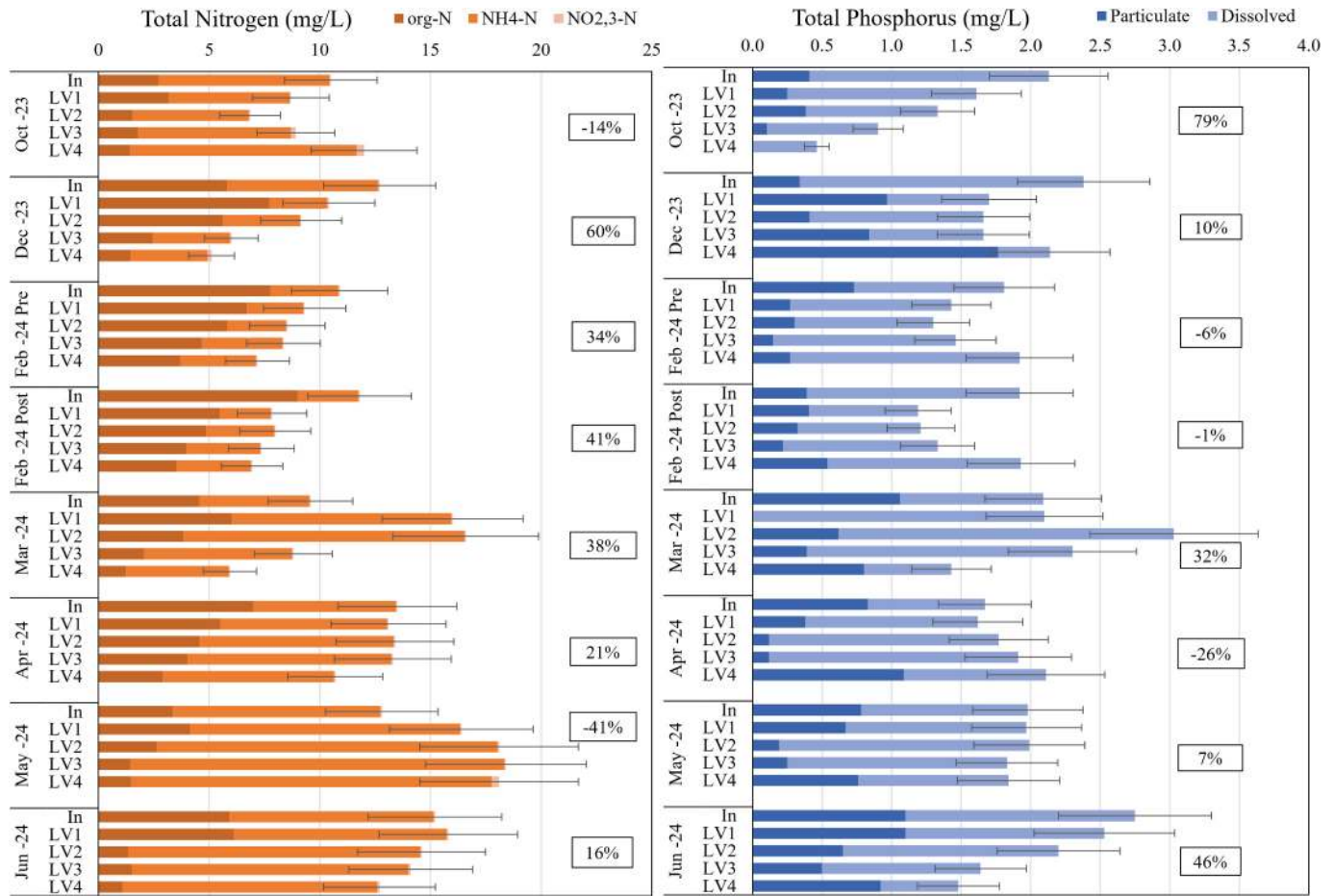


Fig. 4. Influent (In) and effluent concentrations of the respective fractions of tot-N (org-N, NH₄-N, NO_{2,3}-N) and tot-P (particulate and dissolved) from the four levels (LV1–4) of the green wall, with the total removal (%) after LV4. Error bars represent analytical uncertainties of total nitrogen and total phosphorus. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.4. Microbial quality

The pathogenic microorganisms in greywater usually originate from

fecal contamination (e.g., *E. coli*), mucosal and skin sources (e.g., *P. aeruginosa*), food handling (e.g., *Campylobacter*) [15]. The high concentrations of *E. coli* (4.4×10^5 – 6.8×10^6 MPN/100 mL), enterococci

Table 2

The concentration of pathogenic microorganisms in the influents (In) and the effluents from the different levels (LV1–4) of the green wall during the different sampling campaigns March to June 2024. Log₁₀ shows the log reduction of the respective pathogenic microorganisms at each level. NA = not analyzed. *Legionella* spp. in all samples was <10 CFU/100 mL and *Campylobacter* was not detected, therefore not presented in the table.

		Mar		Apr		May		Jun	
			Log ₁₀		Log ₁₀		Log ₁₀		Log ₁₀
<i>E. coli</i> MPN/100 mL	In	6.8×10^6		3.5×10^6		3.9×10^6		4.4×10^5	
	LV1	8.1×10^6	-0.1	5.0×10^5	0.8	1.3×10^6	0.5	3.4×10^5	0.1
	LV2	1.9×10^5	1.6	1.0×10^5	1.5	1.2×10^5	1.5	2.5×10^5	0.2
	LV3	1.0×10^5	1.8	3.0×10^2	4.1	2.4×10^4	2.2	6.1×10^5	-0.1
	LV4	2.4×10^4	2.5	3.0×10^1	5.1	2.4×10^3	3.3	2.6×10^3	2.2
Enterococci CFU/100 mL	In	NA		1.1×10^4		3.2×10^3		1.4×10^4	
	LV1	NA	-	1.8×10^3	0.8	1.0×10^3	0.5	7.2×10^3	0.3
	LV2	NA	-	1.6×10^2	1.8	3.0×10^2	1.0	8.2×10^3	0.2
	LV3	NA	-	1.0×10^0	4.0	3.0×10^2	1.0	1.7×10^3	0.9
	LV4	NA	-	5.0×10^0	3.3	1.8×10^1	2.3	7.7×10^1	2.2
<i>P. aeruginosa</i> MPN/100 mL	In	4.6×10^4		3.1×10^4		1.2×10^4		8.5×10^3	
	LV1	1.2×10^4	0.6	2.4×10^3	1.1	3.4×10^3	0.5	7.1×10^3	0.1
	LV2	1.3×10^3	1.5	4.6×10^2	1.8	1.1×10^3	1.0	5.8×10^3	0.2
	LV3	9.8×10^2	1.7	1.0×10^0	4.5	3.1×10^2	1.6	1.6×10^3	0.7
	LV4	2.9×10^2	2.2	1.0×10^0	4.5	3.0×10^1	2.6	2.1×10^1	2.6
<i>C. perfringens</i> CFU/100 mL	In	NA		7.2×10^3		8.0×10^3		5.5×10^5	
	LV1	NA	-	3.9×10^3	0.3	7.2×10^3	0.0	1.3×10^5	0.6
	LV2	NA	-	4.1×10^2	1.2	2.2×10^3	0.6	2.2×10^5	0.4
	LV3	NA	-	1.7×10^2	1.6	9.0×10^2	0.9	2.8×10^5	0.3
	LV4	NA	-	1.0×10^2	1.9	2.3×10^2	1.5	1.0×10^3	2.7

(3.2×10^3 – 1.4×10^4 CFU/100 mL), *P. aeruginosa* (8.5×10^3 – 4.6×10^4 MPN/100 mL), and *C. perfringens* (7.2×10^3 – 5.5×10^5 CFU/100 mL) detected in the influent greywater (Table 2) which were in the range of reported concentrations observed in previous studies (Table 3). In terms of removal, the green wall achieved a log₁₀ removal of 2.2–5.1 for *E. coli*, 2.2–4.0 for enterococci, 2.2–4.5 for *P. aeruginosa*, and 1.5–2.7 for *C. perfringens* (Table 2). These removal efficiencies were relatively higher than the removal efficiencies observed for greywater treatment systems in previous studies, especially for the case of *P. aeruginosa* (0.7–4.2 log₁₀), and *C. perfringens* (0.2–2.0 log₁₀) (Tables 2 and 3). Each level of the green wall contributed to the total removal of the pathogenic microorganisms studied, especially LV4 (Table 2). The coarser LECA filter material in LV1 showed similar removal efficiency as the other subsequent levels, LV2 and LV3, with the finer biochar-pumice mix filter material. However, the effluent concentrations from LV4 showed that the pathogenic microorganisms were not completely removed, e.g., effluent concentrations for *E. coli* ranged from 3.0×10^1 – 2.4×10^4 (Table 2). The green wall was operating under horizontal flow with saturated conditions, which can have lower removal efficiency compared to a vertical flow system, with unsaturated conditions as observed previously [23]. In comparison to previous studies (Table 3), the removal efficiency of the green wall was higher without any recirculation or disinfection (Table 2). Unlike Winward et al. [23], the results indicated that the change in seasonal temperature did not affect the removal of the pathogenic microorganisms (Table 2).

The influent and effluent concentrations of *Legionella* spp. were below the quantification limit of 10 CFU/100 mL. The bacteriological culture was very difficult to interpret due to the very high presence of other bacteria in the water, which led to heavy microbial background growth interferences, an issue also reported by Blanky et al. [30]. Therefore, it is possible that the presence of *Legionella* spp. in the greywater can be uncertain due to the analytical challenges. In a study by Blanky et al. [30], *Legionella* spp. was detected in 81 % of the samples of raw greywater with an average concentration of 1.2×10^5 CFU/L, and a low Log₁₀ removal of 1.3 was achieved after treatment with a vertical flow constructed wetland and chlorination. On the other hand, in March and April 2024, *Campylobacter* was analyzed but not detected in any of the eight 2000 mL effluent samples from LV1–LV4. This is in line with the results of a study on greywater, where *Campylobacter* was not detected either [23].

3.5. Public health and reuse compliance

It was evident that greywater can consist of a mix of microorganisms with significant concentrations (Table 2), which can be a potential

public health risk through direct exposure or environmental discharge. Exposure to raw or treated greywater and improper hygiene practices may cause diarrhea, urinary tract infection, skin infection, gastroenteritis, or food poisoning, and therefore, proper hygienisation step (e.g. UV disinfection) is recommended [15]. Generally, *E. coli* has been used as a primary indicator of fecal contamination for microbial water quality. However, reliance solely on *E. coli* may not sufficiently represent the range of microbial risks, particularly due to its susceptibility to environmental regrowth and die-off dynamics influenced by factors such as organic matter, nutrients, and temperature [15,23,28].

Enterococci are more stable in the environment and show a stronger correlation with fecal contamination, especially in aquatic environments like ponds, making them a valuable supplementary indicator [31]. In addition, the opportunistic pathogens *P. aeruginosa* [15,30] and *C. perfringens* [23,32] are known for their persistence in treated greywater and resistance to disinfection methods (i.e., UV or chlorination). *P. aeruginosa* can also regrow under favorable conditions and can be a relevant indicator for opportunistic pathogens [23]. One study found high concentrations of *P. aeruginosa* in treated greywater where *E. coli* was absent [30]. Moreover, *C. perfringens* can be a suitable indicator for the presence of protozoan pathogens such as *Giardia* and *Cryptosporidium*, as well as enteric viruses [23,32]. Therefore, including enterococci, *P. aeruginosa*, and *C. perfringens* as an alternative or supplementary to *E. coli* can improve the reliability of microbial water quality assessments and help develop policies on reuse compliance and public health safety guidelines.

The European Commission has categorized the minimum requirement for the reuse of reclaimed water in agriculture. The Class A category, which permits irrigation of all food crops consumed raw, including those with edible parts in direct contact with the reclaimed water or grown below ground, requires BOD and TSS to be ≤ 10 mg/L, turbidity ≤ 5 NTU, *E. coli* ≤ 10 CFU/100 mL, and *Legionella* spp. ≤ 1000 CFU/L (where aerosol exposure is a concern) [44]. However, only *E. coli* concentrations are considered relevant in other categories defined by the European Commission, Classes B (≤ 100 CFU/100 mL), C (≤ 1000 CFU/100 mL), and D ($\leq 10,000$ CFU/100 mL), as these classes involve crops with lower exposure risk or irrigation methods with no direct contact with edible plant parts. A hygienisation step (e.g., UV disinfection) is also mandatory to fulfill the EU regulation for reuse in agriculture. The overall quality of the final effluent from the green wall did not meet the above requirements, especially with regard to *E. coli* (3.0×10^1 to 2.4×10^4 MPN/100 mL) (Table 2). The *E. coli* concentration was also higher than the 500 CFU/100 mL, which is a requirement for excellent bathing water quality for inland waterbodies [34]. Some countries have more stringent or relaxed *E. coli* requirements for irrigation, e.g., Australia

Table 3

Influent concentrations of pathogenic microorganisms in raw greywater and the removal efficiency by different treatment systems found in the literature. * Concentrations in MPN/100 mL.

Microorganisms	Concentrations (CFU/100 mL)	Log ₁₀	Greywater source	Treatment system	Reference
<i>E. coli</i>	0.02– 6.3×10^6	0.7–1	residential area	activated sludge and biofilter	[31]
Enterococci	0.01– 1.26×10^5	0.7–1			
<i>C. perfringens</i>	0.02– 6.3×10^4	0.2–0.3			
<i>E. coli</i>	0.6 – 6.3×10^3	2.0–2.8	student dormitory	horizontal flow reed bed, vertical flow reed bed	[23]
Enterococci	631 ± 8	1.6–2.3			
<i>P. aeruginosa</i>	2.5×10^4	2.9–4.2			
<i>C. perfringens</i>	1.2×10^3	1.4–2.0			
<i>P. aeruginosa</i>	$3.3 \pm 3.1 \times 10^3$	1.4	residential building	rotating biological contactor	[32]
<i>C. perfringens</i>	4.6 ± 5.7	0.8			
<i>E. coli</i>	$1.4 \pm 3.4 \times 10^5$	2.5	residential area	recirculating horizontal constructed wetland	[28]
<i>P. aeruginosa</i>	$0.7 \pm 1.7 \times 10^3$	0.7			
Enterococci	$0.6 \pm 1.3 \times 10^4$	2.2	Single and multi-family houses	reticulating vertical flow constructed wetland + Cl ₂	[30]
<i>P. aeruginosa</i>	$0.5 \pm 1.3 \times 10^4$	1.2			
<i>E. coli</i> *	$1.3 \pm 0.0002 \times 10^5$	0.66	single family house	aerobic biochar filter	[33]
Enterococci*	5.9 ± 5.6	–1.44			
<i>E. coli</i> *	0.2 – 1.3×10^6	5.1	student dormitory	biofilter + green wall + recirculation	[18]
<i>E. coli</i>	$>1.0 \times 10^5$	2.2–4.0	urban city district	green wall	[21]
Enterococci	0.7 – 4.2×10^4	2.2–4.0			

(<1 CFU/100 mL), and Italy (100 CFU/100 mL) [16]. Studies have suggested the option of greywater reuse in low human contact applications such as subsurface drip irrigation, groundwater recharge, or dilution with freshwater used for irrigation [13,15]. One study found a substantial reduction in *E. coli* and enterococci in natural treatment systems such as ponds [31]. However, such pond systems should be fenced to restrict public access and prevent bathing, and additional hygienisation measures should be implemented to minimize microbial risks [31]. The Brannäs wetland in Örsbaken, Sweden, established in 1993, currently serves as a tertiary treatment system for wastewater (Oxelö [35]). This wetland has significantly enhanced local biodiversity, particularly birdlife. In addition to its ecological benefits, the wetland features a hiking trail that adds recreational value to the area (Oxelö [35]). Therefore, the release of green wall effluent into recreational waterbodies may warrant further investigation to assess whether public health safety can be ensured, such as through fencing the system or implementing hygienisation methods like UV treatment or ozonation.

3.6. Vegetation growth

Based on visual assessment, among the total 17 plant species, including the planted species in August 2023, 11 species (*Armeria maritima*, *Carex nigra*, *Eriophorum angustifolium*, *Lythrum salicaria*, *Hedera Helix*, *Menyanthes trifoliata*, *Comarum palustre*, *Carex appressa*, *Caltha palustris*, *Iris sibirica*, and *Zantedeschia aethiopica*) demonstrated good resilience and survivability in the biochar-pumice filter media irrigated with greywater. *Armeria maritima*, *Carex nigra*, *Eriophorum angustifolium*,

Lythrum salicaria, *Hedera Helix*, and *Menyanthes trifoliata* had green leaves even during the colder months, October 2023–March 2024 (below 10 °C) (Fig. 5) and even during the months when the filter media was frozen. *Comarum palustre*, *Carex appressa*, *Caltha palustris*, and *Iris sibirica* were dormant during the colder months but flourished and showed fast growth when the seasonal temperature started to rise in late March 2024. The *Lythrum salicaria*, *Menyanthes trifoliata*, *Comarum palustre*, and *Carex nigra* species were observed to propagate in the filter media when comparing May and August of 2024 (Fig. 5). As the air temperature rose after March 2024, the flowering plant species *Armeria maritima*, *Lythrum salicaria*, and *Menyanthes trifoliata*, *Comarum palustre*, *Caltha palustris*, and *Iris sibirica* bloomed, and *Eriophorum angustifolium* bloomed in August 2024. *Zantedeschia aethiopica* was thriving until December 2023 and bloomed. However, the species died during the following winter and may not be suitable for this kind of application in the Scandinavian climate.

The vegetation did not have significant (Kruskal-Wallis H test, $n = 8$) influence on the treatment efficiency of the green wall. Also, during April, May, and June of 2024, when the plants flourished and grew (Fig. 5), the treatment efficiency was unaffected. Previously, a study on a green wall for greywater treatment in Australia found plant species including *Canna lilies* and *Carex appressa* to be effective in removing nitrogen and phosphorus [36,37]. Similarly, in another study from Austria, *Eriophorum vaginatum* and *Lythrum salicaria* were reported as suitable in green walls for greywater treatment [29]. However, like Dal Ferro et al. [17], the results of this study contradicted the observation from previous studies. Nevertheless, vegetation in green wall systems



Fig. 5. Sequence of photos of the green wall from the establishment phase in June 2023 until the end of the experiment in August 2024 to assess the vegetation growth, die-off, and regrowth. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

can still contribute to aesthetics, microclimate regulation, air purification, noise reduction, and urban biodiversity [29,38,39].

In addition, previous studies have reported concern for detrimental effects on soil properties and chlorosis (brown patches on leaves) on plants associated with salinity of greywater [27,40,41]. The overall concentrations of sodium and chloride in the influent and the effluent remained relatively constant during the study (Table 1), and detrimental effects on the vegetation were not observed based on visual assessment of the plants in this green wall study.

3.7. Practical challenges

The vertECO® system was designed to operate with horizontal saturated subsurface flow, which can be challenging when filter materials with low hydraulic conductivity (e.g., biochar) are used. Comparing the flow rates of 750–1400 L/d [22] and 500 L/d [42] investigated using the vertECO® system, the flow rate of this study, 430 L/d, was relatively low, which is less than a single household greywater generation (5 P.E., 96 L/p/d). However, if it is possible to change the design of the vertECO® system to vertical flow feeding, then it can provide aerobic conditions due to intermittent loading, possibly increase hydraulic conductivity of the filter material, resulting in enhanced treatment performance and allowing for a smaller wall area per person [43].

According to the particle size distribution, 90 % of the biochar-pumice mix particles were below 3.18 mm, which was lower than those used in previous studies using the vertECO® system, e.g., LECA 8–16 mm [22] and LECA 8–16 mm with 4–8 mm gravel, zeolite, and crushed expanded clay [42]. The BOD treatment performance of the LECA in LV1 was very similar to the subsequent biochar-pumice mix LV2–LV4 (Fig. 3). Therefore, using only LECA or increasing the proportion of pumice in the biochar mix could potentially enhance hydraulic conductivity, support higher flow rates, and reduce issues related to clogging and ponding. Alternatively, different levels of the vertECO® system could be filled with varying sizes and ratios of filter materials, as studied by Vobruba et al. [42].

The aeration system of the vertECO® system included a perforated tube at the bottom of each level and connected to an air pump (Fig. 1). However, in this study, it was assumed that the perforations were blocked by particles of the filter media (fines of the biochar), resulting in low oxygen levels in the beds, which may have affected the nitrification. Washing the filter materials (biochar and pumice) prior to use could help reduce finer particles that may block the perforations in the aeration tubes. In addition, a layer of coarser material (e.g., gravel) on top of the aeration tube may reduce the chance of clogging the perforations. A functioning aeration system could also help the vertECO® system during the freezing periods by pumping warmer air (room temperature) into the different levels.

The stainless-steel structure of the vertECO® system may not be suitable for colder climates, as the material can contribute to faster cooling and initiate freezing of the water inside the green wall. Initially, a winter with such prolonged subzero temperatures (10–20 days) (Fig. 2) was not expected at the study site (RecoLab, Helsingborg). Analyzing the air temperature data of Helsingborg from 2014 to 2024 from the Swedish Meteorological and Hydrological Institute (www.smhi.se), only January 2021 experienced more than 14 consecutive days below freezing. For observed winter temperatures, thermal cables could be installed in the levels to prevent freezing.

Once the system is set up and running, the operation and maintenance requirements are low. Part of the maintenance was to remove the sludge and clean the pre-sedimentation tanks after several weeks of use. A floating thick scum layer or high deposition at the bottom can otherwise affect the installed pump. Moreover, the inlet and outlet chambers of the vertECO® system (Fig. 1) had low volume capacity, which overflowed during increased flow rates. These chambers were partitioned with perforated barriers to hold the filter media in place,

which may have been susceptible to clogging and flow obstruction, particularly at the top level where raw greywater was introduced. When the pre-sedimentation tanks and the chambers are not covered, they become a breeding site for flies and mosquitoes, and algal growth, which adds to the overall maintenance.

4. Conclusions

This study demonstrated the potential of a green wall as an effective decentralized greywater treatment solution in cool climates such as those in Scandinavia. The green wall system used the vertECO® module that functioned as a saturated subsurface horizontal flow wetland and provided effective removal of organic matter, e.g., BOD (90–97 %) and TOC (75–96 %). However, right after the observed freezing period and before the maintenance in February, the BOD treatment was reduced to 80 %, which was still within the discharge requirement from on-site greywater systems in Sweden. In contrast, the nitrogen and phosphorus removal was poor, and leaching of N and P from the filter media was observed at a few sampling occasions. The low nutrient removal by the green wall may be acceptable, as currently there are no regulations on nitrogen and phosphorus discharge from greywater systems in Sweden. To increase the removal of phosphorus, reactive filter media for phosphorus sorption could be applied, e.g., in the lowest level of the green wall. In the case of microbial quality, the green wall effectively removed *E. coli*, enterococci, *P. aeruginosa*, and *C. perfringens*, with Log₁₀ reductions of 2.2–5.1, 2.2–4.0, 2.2–4.5, and 1.5–2.7, respectively; these removal efficiencies were higher than previously observed (<2.8 Log₁₀ reductions). However, the effluent concentrations of the pathogenic microorganisms were still above the European Commission's requirement for non-potable reuse of reclaimed water (<1000 CFU/100 mL for *E. coli*), indicating the importance of a hygienisation step (e.g., UV disinfection). *Legionella* spp. was below the reporting limit (10 CFU/100 mL), and *Campylobacter* was not detected in any of the influents or effluents. The BOD treatment of the green wall was not impacted by the cold winter temperatures, even when some weeks were sub-zero. In addition, the presence of vegetation showed no influence on the treatment, both during the dormant phase in the colder months and the fast growth phase in warmer months. *Carex nigra*, *Armeria maritima*, *Lythrum salicaria*, and *Menyanthes trifoliata*, *Comarum palustre*, *Caltha palustris*, and *Iris sibirica* were the most resilient plant species, rapidly flourishing and blooming. In summary, the green wall demonstrated the potential to provide effective greywater treatment with a visual aesthetic in an urban environment under the cool climatic conditions.

CRedit authorship contribution statement

Mashreki Sami: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Annelie Hedström:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Elisabeth Kvarnström:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **David T. McCarthy:** Methodology, Conceptualization. **Heinz Gattringer:** Writing – review & editing, Resources. **Marco Hartl:** Writing – review & editing, Resources. **Inga Herrmann:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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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Data availability

The raw dataset is published on the Swedish National Data (SND) Services website and can be found in the following link:

Sami, M., Hedström, A., Kvarnström, E., & Herrmann, I. (2025). *Quality of greywater from an urban city district and treated effluent from an outdoor green wall in Helsingborg* (Version 1) [Data set]. Luleå University of Technology. DOI: <https://doi.org/10.5878/v4nx-3w35>.

Data availability

The data will be published in the Swedish National Database website, and the link to the data is added in the manuscript.

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