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Research article

Resilience to flow variability of an open-air green wall for greywater treatment

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ABSTRACT

Water management in urban areas is challenged by climate change and increasing population, and the reduction of water consumption in urban areas is becoming a major issue. Thus, domestic greywater (GW) can be a valuable water source for non-potable purposes, coupled with the benefits provided by a nature-based treatment approach. In this context, green walls have been proposed for GW treatment and local reuse, hence coupling the advantage of GW reuse with the benefits provided by a nature-based treatment approach. The amount of available GW is linked with the occupancy and habits of the inhabitants, but there is still limited knowledge on the impact of variations of GW flow rate on the treatment efficiency and on the health of the green wall. Therefore, this study aims to test the resilience of a modular green wall to variations in GW flow rate over 7 months. The experiments were performed on two configurations fed with synthetic GW: one was fed with a constant flow rate (equivalent to daily GW production per capita) as a reference, while the other received a variable flow schedule. The variable schedule included three phases: underload (−50 %), overload (+50 %) and maintenance flow. Input and output water were analysed to evaluate the treatment performances on fourteen physical-chemical parameters. Results showed that neither underload nor maintenance caused any detrimental effect on GW treatment efficiency or plants. Overload conditions caused a slight decrease in the treatment efficiency (e.g., 93.8 % for BOD_5 compared to 100 % recorded in the control configuration), and plants exhibited visual signs of distress. However, these negative effects disappeared after re-establishing the standard flow rate. These findings demonstrated the resilience of green walls to inflow rate variations. The results provide useful indications for the application of green walls for GW treatment and provide important indications for design guidelines, in terms of maximum values of organic loading rate (~20 g_{BOD5} m^{-2} d^{-1}) and oxygen transfer rate (~15 g_{O2} m^{-2} d^{-1}), and focusing on building maximum capacity as driving parameter.

1. Introduction

Nature-based Solutions (NbS) can mitigate the impacts of climate change in urban areas by providing ecosystem services and benefits to buildings and neighbourhoods such as thermal and acoustic insulation, reduction of heat island effect, CO_2 removal and biodiversity preservation (Bustami et al., 2018; Medl et al., 2017; Oral et al., 2020). Rain gardens, green roofs and green walls are NbS becoming highly appreciated elements in urban design, whose implementation is also recommended by EU policies (European Commission, 2015). Even though these NbS are usually designed to minimize their daily water demand to manage dry periods, enhancing NbS presence in urban areas will increase the demand for water for irrigation (Nouri et al., 2019). The reuse of reclaimed greywater (GW), i.e., the portion of household wastewater that excludes toilet flush, can be an effective way to avoid the increase in demand for clean water. Light GW, which also omits wastewater from kitchen sinks, is produced in large amounts (around 100 L d^{-1} per capita in European Western countries) and is characterized by low concentrations of contaminants compared to household wastewater (Boano et al., 2020). Light GW is thus suitable for reuse after a relatively mild treatment to remove contaminants (Ghaitidak and Yadav, 2013).

Among NbS for greywater treatment, green walls are well-matched for densely inhabited areas where the lack of space is a limit to the

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application of other NbS. The interest in green walls for GW treatment has increased during the last decade; since the first studies (Gattringer et al., 2016; Masi et al., 2016) many efforts have been devoted to understanding how to optimize their technical features and improve GW treatment efficiency. Practical recommendations on design have been proposed for elements such as filter media, plant species, and green wall heights. As to filter media, studies on different materials have recommended the use of a mixture of fast and slowly draining materials (Boano et al., 2021a; Lakho et al., 2021; Prodanovic et al., 2017). The inclusion of high-performing filter media has also been suggested to improve GW treatment (Boano et al., 2021b; Costamagna et al., 2023). Regarding plants, some studies identified high-performing species (Prodanovic et al., 2019a, 2019b). However, other authors (Dal Ferro et al., 2021) found no significant differences in pollutants removal performances for different plant species, supporting the major contribution to greywater treatment of microbial biofilm compared to plants. Green wall height was also investigated, with emphasis on the minimum number of lines necessary for an effective treatment of greywater (Costamagna et al., 2022; Prodanovic et al., 2020). In addition to wastewater treatment technical assessment, the economic sustainability (Estelrich et al., 2021) and life cycle assessment (Lakho et al., 2022) of full-scale green walls were explored, also quantifying the benefits in terms of air quality improvement and thermal insulation of the building (Lakho et al., 2022; Pucher et al., 2022). Despite the considerable efforts that have been performed in the last years, several knowledge gaps related to robustness and resilience to variations in operational conditions still hamper the use of green walls for GW treatment. Specifically, the inflow rate of GW can exhibit fluctuations due to changes in building occupancy (e.g., during holidays) and to residents' habits. Hourly variations in flow rate are expected to be buffered due to the presence of a degreasing tank, while sustained flow variations lasting for days may impact the performance of the green wall. Previous studies analysed variations in feeding flow rate (Prodanovic et al., 2019a; Sami et al., 2023) applying relatively low values of Hydraulic Loading Rate (HLR; first level: 50–210 L m^{-2} d^{-1}, total: 15–70 L m^{-2} d^{-1}). Information on variations of GW flow for green walls fed with high HLR values are thus still missing. Moreover, there is currently a lack of indications for the design of green walls for GW treatment compared to other more mature NbS (i.e., constructed wetlands) that hamper the application of green walls for GW treatment and reuse.

This study was performed with two main objectives: (i) evaluating the impact of high HLR variations on treatment performances and system robustness of an outdoor green wall; (ii) providing design indications based on conventional design parameters for vertical flow constructed wetlands (VF), which represent the closest well-established technology of NbS for GW treatment.

In detail, the robustness of the outdoor green wall was tested comparing the applied HLR (equivalent to daily GW production of 96 L per capita, which leads to a high HLR for this type of systems) with −50 % underload and +50 % overload inflow rates. The treatment performances of the green wall have been evaluated through 14 physico-chemical and biological parameters over 7 months. Potential damage to plants was visually assessed. To the authors' knowledge, no other studies have been performed in open-air environment with a focus on green wall robustness to high variations in HLR that may occur in full-scale applications.

Moreover, a comparison between vertical subsurface flow constructed wetlands (VF) and the tested green wall has been performed to identify differences and similarities between green walls and VF. These two systems share a similar hydraulic behaviour, and the knowledge from the well-established VF field can thus provide useful information for the less mature field of green walls for GW treatment in terms of guidelines and performance evaluation. Specifically, the comparison was done in terms of conventional design parameters, such as oxygen consumption rate (OCR), HLR, and organic loading rate (OLR). The findings provide valuable indications for the design of green walls for GW treatment and reuse, such as values of OCR and OLR that could be used for dimensioning the system.

2. Methods

2.1. Filter medium

The filter medium of a green wall must fulfil some constraints in terms of weight and permeability to be suitable for GW treatment without excessive structural load. Based on previous studies exploring the modular design of a pot-based green wall (Boano et al., 2021a; Costamagna et al., 2023), a 1:1 v/v mixture of coconut fibre and perlite has been selected as a filter medium. The hydraulic conductivity of this medium was tested before installation with a constant head permeameter. In detail, 0.25 m of filter medium was placed in a cylindrical column (0.05 m diameter and 0.1 bar imposed pressure), and the saturated hydraulic conductivity was calculated using Darcy's equation involving five replicates.

2.2. Experimental setup

The experimental setup was part of the outdoor modular green wall built in the Hydraulics Laboratory at Politecnico di Torino for previous studies (Boano et al., 2021a, 2021b; Costamagna et al., 2022, 2023). In this case, two sets of 9 pots (hereinafter denoted as *configuration*; Fig. 1) were organized in three identical columns and analysed considering the columns as replicates for statistical purposes, while the three levels (defined as L1, L2 and L3 from top to bottom) hosted different ornamental plant species (L1: *Carex morrowii*, L2: *Hedera helix*, L3: *Lonicera nitida*). The use of multiple species reduces the risk of phyto-diseases, increases biodiversity and favours aesthetical appearance (Castellar da Cunha et al., 2018). These species have been already tested in previous

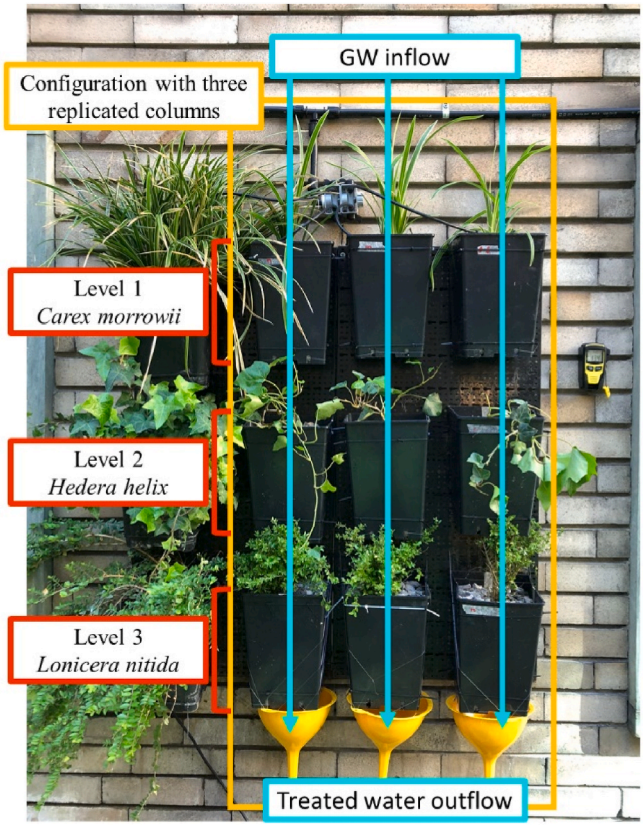

Fig. 1. A configuration of the green wall used for the stress tests at the beginning of the experiments.

studies to be resistant to soil moisture and GW feeding, and have been shown to survive years after the end of the studies (Boano et al., 2021a, 2021b; Costamagna et al., 2022, 2023). Each pot (height 0.25 m, width decreasing from 0.17 m at the top to 0.14 m at the bottom; Fig. 1) was filled with 5 L of filter medium, hence resulting in a 0.02 m freeboard space on top of the medium.

During the tests, GW was fed to the top pots and percolated downwards through 16 holes at the bottom of each pot (1 cm diameter, protected by a metallic net). Synthetic GW adopted to favour experimental reproducibility, as in other studies (Bakheet et al., 2020; Boano et al., 2021a; Fowdar et al., 2017; Kotsia et al., 2020; Prodanovic et al., 2017). It was prepared every 2 days and stored in a 1.5 m^3 HDPE tank using commercial products as detailed in the Supplementary Materials (Tables S–I). Then, a pump mixed the tank every hour and supplied GW to each pot through a pressurized irrigation system of plastic pipes connected to flow-controlled drippers.

Before the experiments, a pre-washing procedure was applied to remove fine particles from the filter medium and fully hydrate it. In detail, both configurations were washed with 128 L of tap water over four days (4 L d^{-1} per column, 8 h per day), monitoring electric conductivity, temperature and pH (Boano et al., 2021a).

Then, the two configurations involved in the study received different feeding schedule: one configuration was engaged in the hydraulic stress tests, the other was a control constantly fed with a standard flow rate to provide reference. The standard flow rate was set to 24 L d^{-1} per column and was provided as 1-L flushes for 15 min followed by 45-min drainage phases. The value of the standard flow rate corresponds to the average daily production of GW per capita which should be treated through a single panel of the modular green wall (Boano et al., 2020; Ghaitidak and Yadav, 2013). The standard flow rate resulted in a hydraulic loading rate (HLR) of 871 L m^{-2} d^{-1} on the first level, which corresponds to the highest range of HLRs in vertical constructed wetlands and green walls for water treatment (Boano et al., 2020; Castellar da Cunha et al., 2018; Dotro et al., 2017). The configuration dedicated to the hydraulic stress tests according to the schedule in Table 1, which was adapted from the Austrian guidelines for small wastewater treatment plants (EN 12566-3:2016, 2016). The schedule began with a standard flow phase to establish steady-state conditions in the green wall, and to observe the natural variations in the efficiency of GW treatment. Then, two types of stress conditions were simulated, i.e. underload (−50 % flow) and overload (+50 % flow) events, respectively corresponding to a decrease and increase of the GW equivalent inhabitants feeding the green wall. Each stress condition has been applied for three weeks, followed by three weeks of standard flow to monitor the return to pre-stress conditions. Moreover, a phase of maintenance flow (0.5 L d^{-1} $column^{-1}$) was also considered to simulate a third type of stress event due to a strong reduction in GW supply to the green wall (e.g., during summer in a continental climate). All these feeding programs provided much more water than the contribution of precipitation in Turin, which corresponded to a yearly total depth of 843 mm, with a maximum daily precipitation of 73.6 mm d^{-1} during the monitoring period. The contribution of evapotranspiration was also negligible, as confirmed by the weekly comparison of inlet and outlet water volumes during the sampling days.

The efficiency of GW treatment was assessed (section 2.3) and plant health was visually evaluated throughout the whole duration of the study, equal to 7 months. The number of weeks detailed in Table 1 were accounted in sequence.

2.3. Water sampling and data analysis

Input GW and output water samples have been collected weekly from each pot from May to November (304 samples in total). The test period was selected to expose the outdoor green wall to summer and winter external temperatures. Physicochemical and biological parameters were measured on-site and within 12 h from sampling in the Circular Economy Lab at Politecnico di Torino. For each sample, GW flowing from the bottom of each pot was collected in an aluminium tray and it was then transferred to an 800 mL plastic bottle. Total suspended solids (TSS) were analysed by filtering up to 700 mL of water sample through 0.45 μm cellulose membranes. Due to the time needed for water collection and filtering, GW samples for TSS determination were collected and measured one day before the other samples. On the following day, 500 mL of GW were collected from the outflow of each pot to quantify the other parameters. Dissolved oxygen (DO), pH, temperature (T), and electrical conductivity (EC) were measured on-site using a WTW Multi 3320 portable probe. BOD5 was measured with a respirometric method through a VELP FOC 215E cooled incubator equipped with BOD sensor systems. Chemical oxygen demand (COD), total nitrogen (TN), nitric nitrogen (NO_3^--N), ammonia nitrogen (NH_4^+-N), total phosphorus (TP), chloride (Cl^-), and methylene blue active substances (MBAS, i.e., anionic surfactants) were analysed with Nanocolor™ reagent kits, a VELP COD ECO 16 thermoreactor (for TN, TP, and COD), and a model AL450 Multidirect photometer (details in Table X SI). Total coliforms (TC) were measured weekly between October and November (6 sampling dates during and after the overflow period) with the IDEXX Colilert-18 procedure. For TC determination, 100 mL of GW were collected in sterile containers from a single pot per level of each configuration.

For each parameter, concentration values below the detection limit (DL) were set equal to the DL for the data analysis (values in Table S-II). The average value at the outflow of each level was calculated for both configurations at all sampling dates. The cumulative removal efficiency at the *i*-th level was evaluated for all laboratory parameters as

$$E_i = \frac{C_{GW} - C_{level_i}}{C_{GW}} \times 100 \quad (1)$$

where C_{GW} and C_{level_i} represent concentrations in input GW and the outflow of the *i*-th level, respectively. The mass removal rate of each contaminant by the *i*-th level was calculated as

$$R_i = Q \times \left(C_{GW} - C_{level_i}\right) \quad (2)$$

where Q is the flow rate.

Values of common design parameters used for vertical constructed wetlands were also determined. Oxygen consumption rates of the *i*-th level (OCR_i) and of a column (OCR_{tot}) were calculated based on BOD_5

Table 1
Flow rate schedule of the variable load configuration. Values of underload and overload are inspired by (EN 12566-3:2016, 2016).

Phase	Flow rate (L d^{-1} $column^{-1}$)	HLR (L m^{-2} d^{-1})		Weeks	No. of samples
		First treatment level	Total treatment surface		
Standard	24.0	871	290	5	2
Underload	12.8	472	157	3	3
Standard	24.0	871	290	3	3
Summer maintenance	0.5	18	6	9	–
Standard	24.0	871	290	2	2
Overload	36.8	1335	445	3	3
Standard	24.0	871	290	3	3

(Nivala et al., 2013) with equations (3) and (4). For this analysis, values for the six replicates of the control configurations and variable load configuration were considered separately (i.e., instead of being averaged) to increase the number of data points giving robustness to the analysis.

$$OCR_i = \frac{Q \times \left[\left(C_{level\ i-1,BOD5} - C_{level\ i,BOD5}\right) + 4.3\left(C_{level\ i-1,NH4+} - C_{level\ i,NH4+}\right)\right]}{A} \quad (3)$$

$$OCR_{tot} = \frac{Q \times \left[\left(C_{GW,BOD5} - C_{level\ 3,BOD5}\right) + 4.3\left(C_{GW,NH4+} - C_{level\ 3,NH4+}\right)\right]}{A_{tot}} \quad (4)$$

where $C_{GW,COD}$, $C_{GW,BOD5}$, and $C_{GW,NH4+}$ are the COD, BOD_5 and NH_4^+-N concentrations in input GW, $C_{level\ i,COD}$, $C_{level\ i,BOD5}$, and $C_{level\ i,NH4+}$ are the COD, BOD_5 and NH_4^+-N concentrations outflow of the *i*-th level, A is the surface area of a single level of pots and A_{tot} is the total pot area of all levels.

Hydraulic and organic loading rates (HLR and OLR, respectively) were calculated as:

$$HLR = \frac{Q}{A} \quad (5)$$

$$OLR = \frac{Q \times \left(C_{GW,BOD5} - C_{level,BOD5_i}\right)}{A} \quad (6)$$

Volumetric values of OCR, HLR, and OLR were also estimated using equations (3)–(6) and replacing the surface area of the pots A with the pot volume.

2.4. Statistical analysis

The non-parametric Mann-Whitney *U* test was performed to identify statistically significant differences in removal efficiencies between the variable load configuration and the control configuration during the six phases listed in Table 1 (excluding the maintenance period when samples were not collected). All pots of a specific level in the variable load configuration were compared to the corresponding pots in the control configuration, with at least 12 data points in each phase. The significance of the test was set at $p = 0.05$.

3. Results and discussion

The results have been organised to provide useful design information on different aspects tested during this study: firstly, the characteristics and response of the filter medium are presented in section 3.1. Then, the treatment performances are evaluated in comparison with similar green wall systems and previous studies in section 3.2. Finally, robustness is discussed in section 3.3-3.4 according to the VF design guidelines, in order to leverage the similarities of the two systems and the established knowledge developed for VF.

3.1. Filter medium

The saturated hydraulic conductivity of the filter medium was $2.42{\cdot}10^{-3}{\pm}4.9{\cdot}10^{-5}$ m/s, as results from the performed permeameter tests. This value is consistent with the expected hydraulic conductivity for a 1:1 mixture of coconut fibre and perlite, according to the identified relationship between perlite content and saturated hydraulic conductivity K_s (Boano et al., 2021a; Prodanovic et al., 2018). The observed K_s is higher (+66 %) than the one of the filter media used in a previous study (Costamagna et al., 2022) due to the higher amount of perlite included in the mixture to decrease the risk of clogging, ensuring enough residence time to favour the biological degradation of organic contaminants. Remarkably, the observed value is in line with the design indications given by guidelines for designing vertical subsurface flow wetlands with coarse sand ($1.6{\cdot}10^{-3}$–$4.0{\cdot}10^{-4}$ m/s; German DWA, 2017; see Nivala et al., 2018), enabling a consistent comparison of the performances of the green wall involved in this study with literature.

The system was pre-washed with tap water to prevent clogging and undesirable coloured water at the outlet due to finest particle. The procedure lasted up to the stabilization of physical and chemical parameters measured on site (Fig. 2). The temperature pattern of input tap water was mainly influenced by air temperature variations and water temperature mildly decreased as water flowed along the columns to the outflow (Fig. 2a). pH values in input water were more constant than in the outputs, which progressively increased and eventually attained a constant value of 7.63 ± 0.29 (Fig. 2b). EC in output water displayed a similar pattern, with a decrease from high EC values (>1000 μS/cm) to a constant value of 458 ± 43 μS/cm (Fig. 2c). These trends in pH and EC suggest that the filter medium evolved towards equilibrium conditions as finer particles were washed away and the coconut fibres are well hydrated.

3.2. Hydraulic stress tests

Temperatures of the samples were clearly influenced by seasonal variations in air temperature, with no significant differences between the two configurations (Fig. 3 top). The seasonal trend in GW temperature was characterised by maximum and minimum values of 28.7 °C and 11.9 °C in summer and winter, respectively. Temperature slightly decreased through sequential levels of the green wall, but the seasonal trend was still evident. These data suggest that these systems can be applied in a wide range of temperature and weather conditions.

Even though dissolved oxygen was below 2 mg/L in input GW for the first 19 weeks, aerobic conditions were found for outflow water at all levels of both configurations (Fig. 3 bottom), with no significant differences between the two configurations. This similarity indicates that the potential for oxygen exchange within the filter medium is high enough to support aerobic conditions even during the overload flow rate. Average concentrations of DO in L1 and L2 were slightly higher than those observed in previous work with a less permeable filter medium (Costamagna et al., 2022) and compared with horizontal flow pot-based systems (Pucher et al., 2022). This finding suggests that the increased hydraulic conductivity of the filter medium and the pots' structure (i.e., the presence of drainage holes at the bottom) favoured the presence of aerobic conditions.

pH values slightly increased from neutral in input GW to slightly alkaline after each level, with no significant difference between the two configurations (Fig. 4 top). The pH range does not compromise the potential reuse of treated GW according to common international regulations and guidelines (pH < 9; Boano et al., 2020) and fits within the optimal range of 6.5–8.5 for nitrogen removal (Yin et al., 2016). EC showed no relevant variation among levels regardless of the concentration in input GW (Fig. 4 bottom). No significant difference in EC between the two configurations was found.

Fig. 5 top shows that the concentration of TSS strongly decreased as GW flowed through the levels of the green wall. The comparison between the two configurations revealed that the overload phase resulted in a significant decrease in the removal efficiency of TSS for the first and second levels ($p = 0.001$ and $p = 0.012$ for L1 and L2, respectively). Specifically, the removal efficiency of the variable load configuration was 32.5 ± 12.4 % (L1) and 84.7 ± 10.6 % (L2) compared with 62.7 ± 17.0 % (L1) and 95.9 ± 4.9 % (L2) of the control configuration, probably due to the higher load of TSS fed to the variable load configuration. However, no significant difference in removal efficiencies was observed for the third level (variable load: 85.8 ± 21.2 %, control: 98.4 ± 0.8 %), reaching and overcoming the performances obtained in other studies (Bakheet et al., 2020; Estelrich et al., 2021; Lakho et al., 2021, 2022; Zraunig et al., 2019). These results show that the third level was able to compensate for the lower removal of the other levels, highlighting the

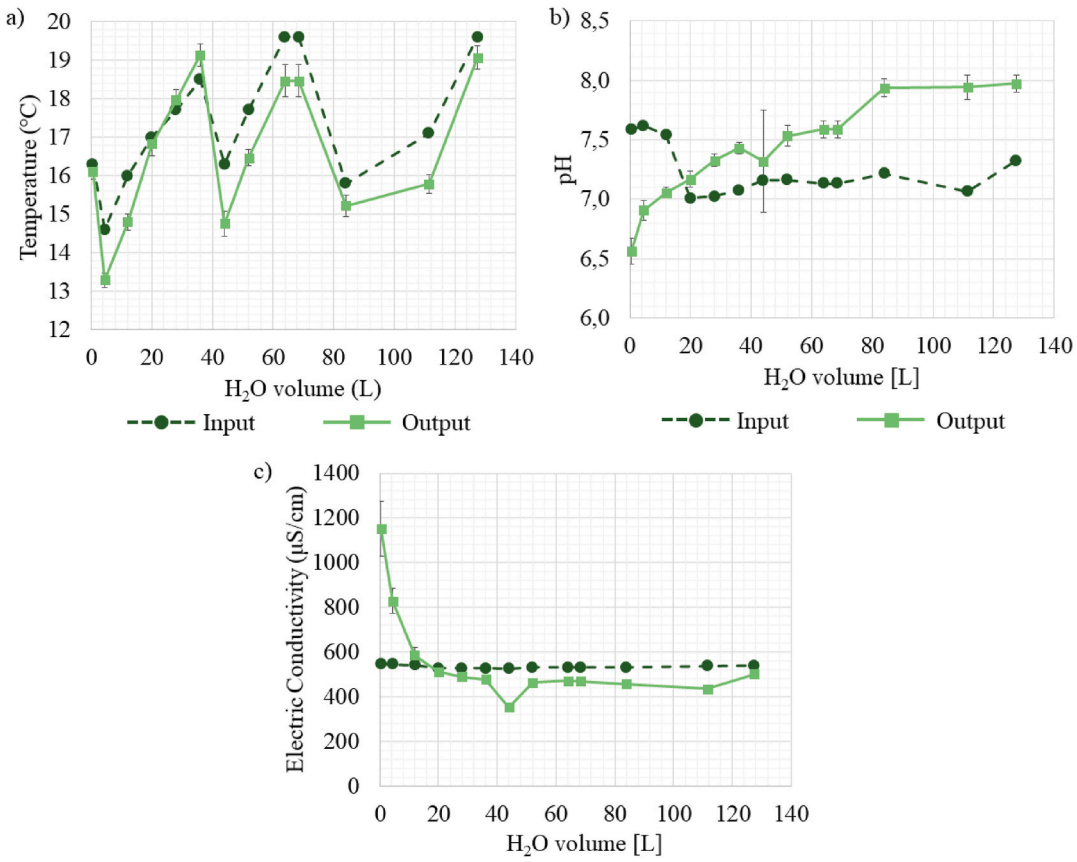

Fig. 2. Parameters measured on the outflow samples during the preliminary washing phase. A) Temperature, b) pH, and c) Electric Conductivity for increasing volumes of washing tap water.

importance of including at least three levels in the green wall structure. Interestingly, the lower removal efficiencies of the variable load configuration in overload conditions are associated with comparable values of mass removal rates of TSS for both configurations (variable load L1 |L2 |L3: 14.8 ± 6.5 mg h^{-1} | 37.8 ± 6.4 mg h^{-1} | 38.8 ± 10.0 mg h^{-1}, control 18.5 ± 6.0 mg h^{-1} | 26.9 ± 3.5 mg h^{-1} | 30.6 ± 0.1 mg h^{-1}; Table S-II) showing high potential of mass removal of the whole system. After the end of the overload flow rate phase, the differences in removal efficiency between the two configurations persisted only for the second level (variable load: 87.0 ± 10.1 %, control: 95.9 ± 3.5 %; p = 0.05), suggesting a progressive recovery from the stress conditions (Tables S–I). These results indicate a very good capacity of the green wall in facing the hydraulic load variations as well as occasional increases in TSS that can derive from specific household habits (e.g., cleaning heavily dirty clothes).

Concentrations of BOD_5 in the two configurations are shown in Fig. 6 top. For the first level, underload flow rate conditions improved the removal efficiency (p = 0.015) of the variable load configuration (89.4 ± 3.0 %) compared to the control configuration (82.0 ± 8.9 %). The same difference was identified for L1 also after the maintenance phase (variable load: 81.0 ± 24.2 %, control: 67.0 ± 21.1 %; p = 0.015). However, these differences were only limited to L1, as no significant difference between the two configurations for L2 and L3 was found in these two phases (Table S-III), proving again the importance of an adequate system size to guarantee high treatment performance in different operational conditions. The higher removal efficiency of the variable load configuration during the underload phase was due to the lower input load BOD_5, as indicated by the lower removal rates compared to the control configuration (Table S-IV). In fact, the opposite behaviour was observed for overload conditions, which significantly decreased BOD_5 removal efficiency for all levels of the green wall. The decrease in removal efficiencies was remarkable at L1 (variable load: 39.4 ± 17.8 %, control: 60.8 ± 20.6 %; p = 0.024) while the difference was lower at L3 (variable load: 93.8 ± 4.7 %, control: 100.0 ± 0.0 %; p = 0.0004), suggesting that the presence of three levels of pots can partially compensate for the loss in treatment efficiency due to an overload. This means that L3 is not only sufficient, as suggested by Prodanovic et al. (2020), but also necessary to guarantee the removal performance in variable working conditions as well as in the entire working life of the system (Costamagna et al., 2022). In terms of mass removal rates, higher values were generally observed for the variable load configuration than for the control one, indicating that the increase in flow rate resulted in stressful conditions for the variable load configuration (Table S-IV). After the end of the overload phase, no difference was found between the two configurations, indicating that the green wall was able to recover from the stress caused by the overload.

Fig. 6 bottom highlights the good removal of COD of both configurations during the whole experiment. However, during the overload phase a decrease in removal efficiency was observed for the variable load configuration (L1: 43.4 ± 17.9 %, L2: 75.3 ± 10.0 %, L3: 84.3 ± 2.7 %) compared to the control configuration (L1: 57.8 ± 15.6 %, L2: 86.7 ± 1.9 %, L3: 86.7 ± 1.9 %). All these differences were statistically significant (p = 0.047, 0.0006 and 0.046 for L1, L2 and L3, respectively). Similarly to BOD_5, the removal rates of COD for the variable load configuration decreased during the underload phase and increased during overload conditions, respectively (Table S–V). The increase in removal rates with increasing GW flow rate indicates that the microbial reactions in the green wall adjusted to the variations in the input load of GW. However, the increase in removal rate in overload conditions was not high enough to compensate for the increase in input load, thus leading to the observed drop in removal efficiency. This behaviour agrees with previous results of numerical simulations of overload in a

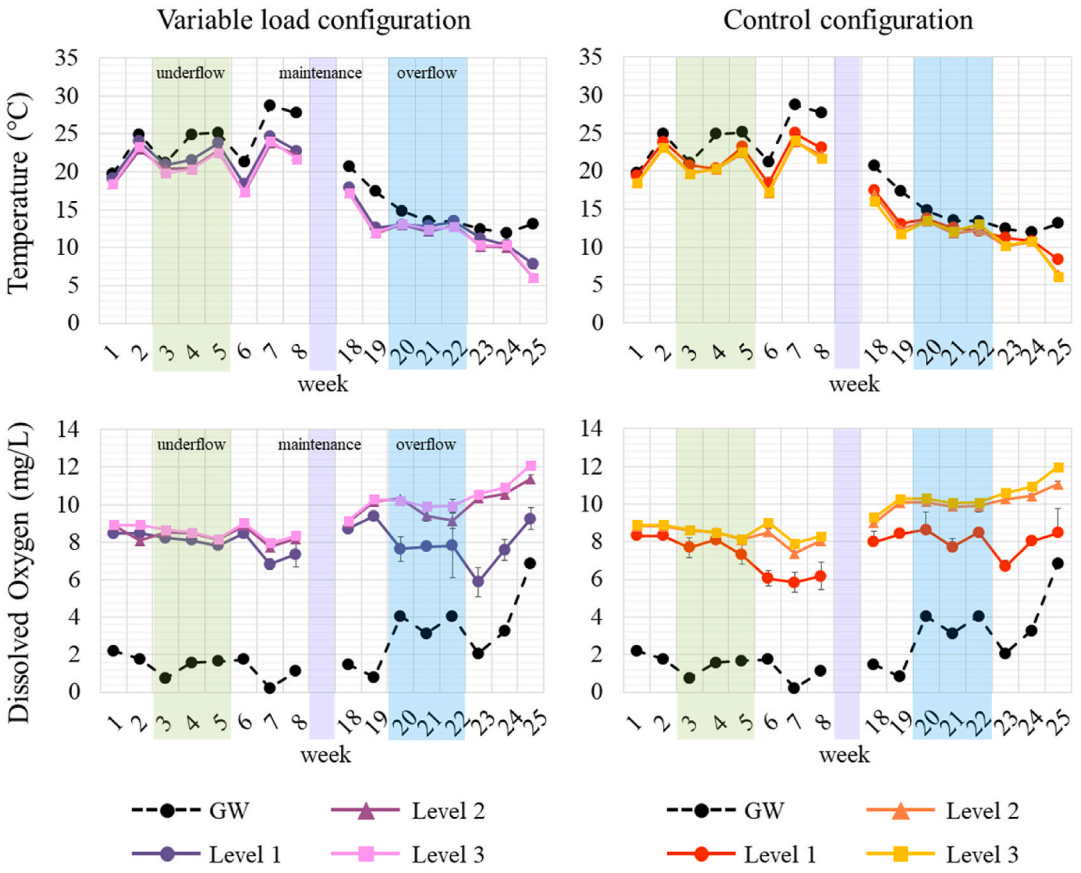

Fig. 3. Observed values of Temperature and Dissolved Oxygen for the two tested configurations for input greywater (GW) and output samples from the three levels. For the variable load configuration, the green, purple and blue backgrounds denote the underload phase (weeks 3–5; HLR = 472 L m^{-2} day^{-1}), maintenance phase (weeks 9–17; HLR = 18 L m^{-2} day^{-1}) and overload phase (weeks 20–22; HLR = 1335 L m^{-2} day^{-1}). For the control configuration, the coloured backgrounds are reported for an easier visual comparison.

constructed wetland (Boano et al., 2018). The differences in COD removal between the two configurations disappeared when the standard flow rate was resumed (Table S-VI).

The removal of MBAS was not affected by the variation in GW flow rate (Fig. 7 top). Both configurations exhibited high performances in MBAS removal at the final outflow in all phases (81.7–98.8 %; Table S-VII). No significant difference in removal efficiency was found between the configurations except for a small but significant decrease for L2 after the end of the maintenance phase (variable load: 94.7 ± 2.5 %, control: 98.3 ± 1.0 %; p = 0.026). Over the whole observation campaign, the average removal efficiency of the variable load configuration was 67.5 ± 26.9 % (L1), 87.4 ± 15.6 % (L2) and 94.1 ± 9.8 % while for the control configuration was 69.9 ± 24.1 % (L1), 91.3 ± 11.9 % (L2) and 95.4 ± 8.9 % (L3). Almost in all levels of both configurations, the MBAS removal was higher than the ones recorded in previous studies with different proportions of filter media. This aspect suggests a possible absorption mechanism due to the higher volume of perlite and a possible decreasing in leaching of natural organic substances due to the lower coconut fibre content (Boano et al., 2021a, 2021b).

TP concentrations exhibited very small variations as GW flowed through the levels of the green wall (Fig. 7 bottom), in line with previous studies (Costamagna et al., 2022; Dal Ferro et al., 2021) that showed very limited removal of TP in the absence of specific sorption materials (Table S-VIII). This should be considered when designing green walls for GW in countries where standards for reuse require strict limits for TP (set below 1–5 mg/L, e.g., Italy, Japan, Slovenia or China; see Boano et al., 2020). On the other hand, the presence of TP can be an advantage when the treated GW is reused for agricultural purposes. A small but significant difference between the configurations was only found in underload conditions for L2 (variable load: 7.7 ± 3.2 %, control: 3.9 ± 3.3 %; p = 0.017) and L3 (variable load: 12.2 ± 2.9 %, control: 7.7 ± 2.7 %; p = 0.004), possibly due to the increase in contact time between GW and filter medium during underload.

Removal of TN was similar for the two configurations regardless of the GW flow rate (Fig. S–1 top). In general, all nitrogen species were characterised by low concentrations (Table S-IX), which in the case of NO_3^--N and NH_4^+-N were often below the detection limit (Tables S-X and S-XI, respectively). Chloride concentrations slightly decreased through successive levels of the green wall (Fig. S–2 bottom), with similar behaviour for the two configurations.

Concentrations of total coliforms (TC) were available since the beginning of the overload phase (Fig. 8). The concentration of TC in the inflow GW (avg ± std: 1.17e8±5.85e7 MPN/100 mL, range: 4.35e7-1.99e8 MPN/100 mL) resulted higher than the usual values that characterise real light greywater (Birks and Hills, 2007) but coherent with the values expected from the original recipe by Diaper et al. (2008). A strong removal of TC was observed for both configurations, with an overall removal of 2-4 orders of magnitude between input GW and the outflow of the third level. These values indicate better performances compared to other vertical green systems in which total coliform data are available in literature (Estelrich et al., 2021; Lakho et al., 2021, 2022). This enhanced removal of TC was probably due to the different substrate volume (pots in the present studies compared to pockets in Lakho et al., 2022, 2021) and flow direction (vertical in the present study compared to horizontal in Estelrich et al. (2021). Even though the concentrations exhibited a large variability, it can be noticed that in overload conditions the removal of TC was lower for the variable load configuration than for the control configuration. These differences were

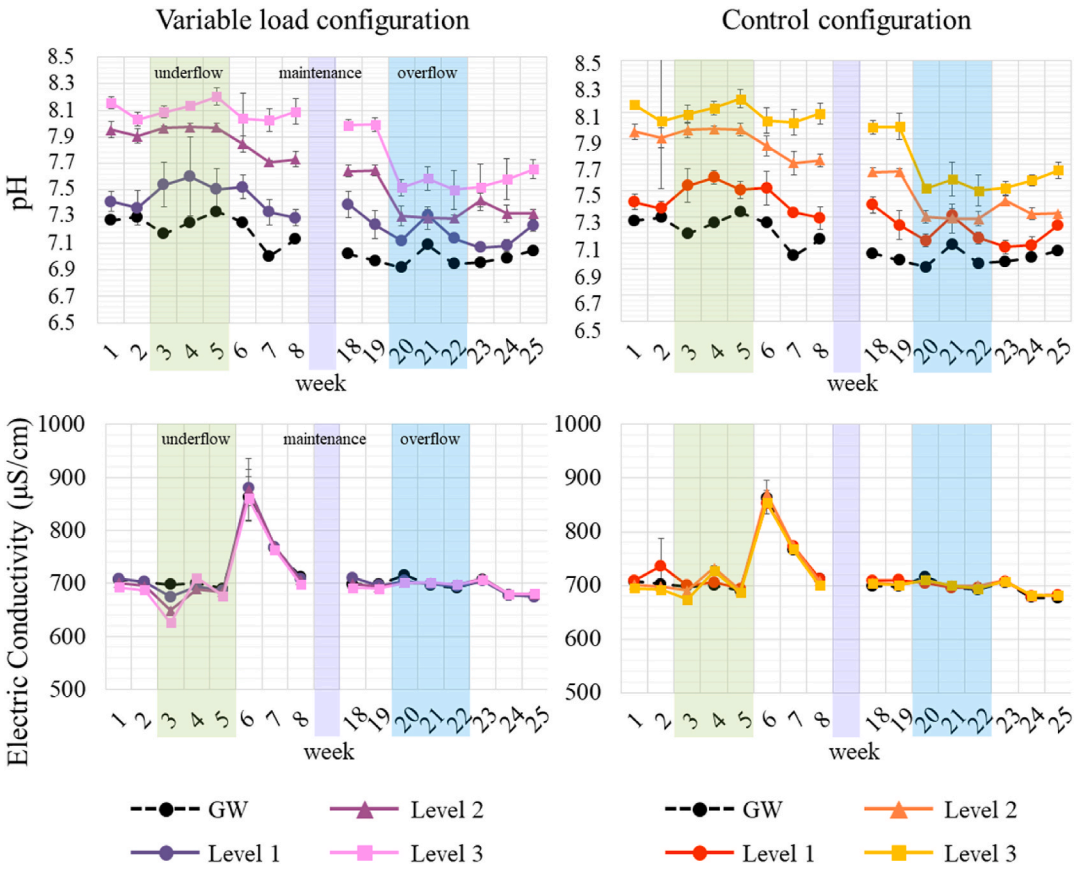

Fig. 4. Observed values of pH and Electric Conductivity for the two tested configurations for input greywater (GW) and output samples from the three levels. For the variable load configuration, the green, purple and blue backgrounds denote the underload phase (weeks 3–5; HLR = 472 L m^{-2} day^{-1}), maintenance phase (weeks 9–17; HLR = 18 L m^{-2} day^{-1}) and overload phase (weeks 20–22; HLR = 1335 L m^{-2} day^{-1}). For the control configuration, the coloured backgrounds are reported for an easier visual comparison.

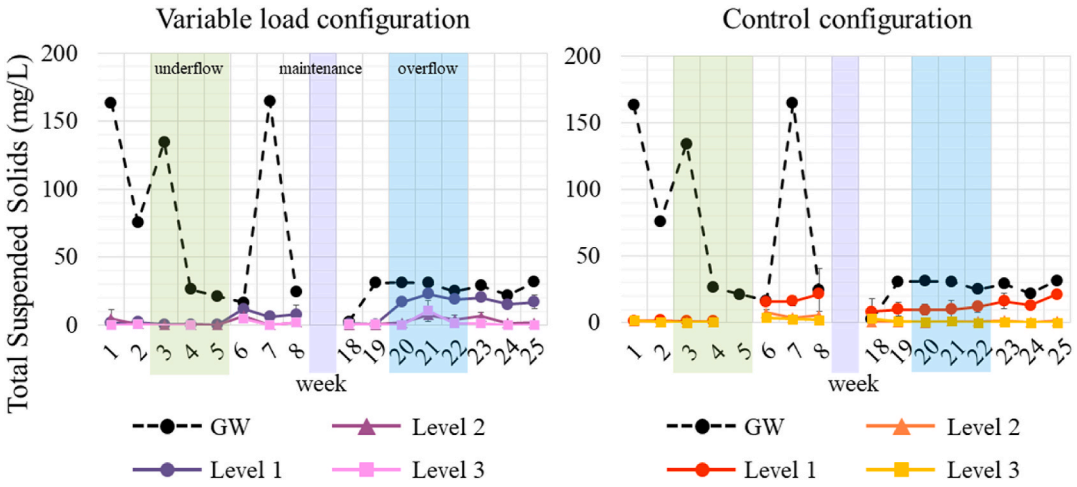

Fig. 5. Observed concentrations of TSS for the two tested configurations for input greywater (GW) and output samples from the three levels. For the variable load configuration, the green, purple and blue backgrounds denote the underload phase (weeks 3–5; HLR = 472 L m^{-2} day^{-1}), maintenance phase (weeks 9–17; HLR = 18 L m^{-2} day^{-1}) and overload phase (weeks 20–22; HLR = 1335 L m^{-2} day^{-1}). For the control configuration, the coloured backgrounds are reported for an easier visual comparison.

no longer observed when the standard flow was applied again to the variable load configuration. These results confirm the previous finding for COD and BOD_5 about the negative impact of overload conditions on the performance of GW treatment.

The visual observation of the plants on the green wall revealed that plants did not disclose any apparent damage during both underload and maintenance conditions. On the other hand, some plants of the variable load configuration showed signs of distress (i.e., wilting of some leaves) during overload conditions, possibly because of the high level of soil moisture and consequent rotting of the roots. However, these plants apparently recovered when the standard flow rate of GW was again applied for two weeks after the end of the overload phase, and no further

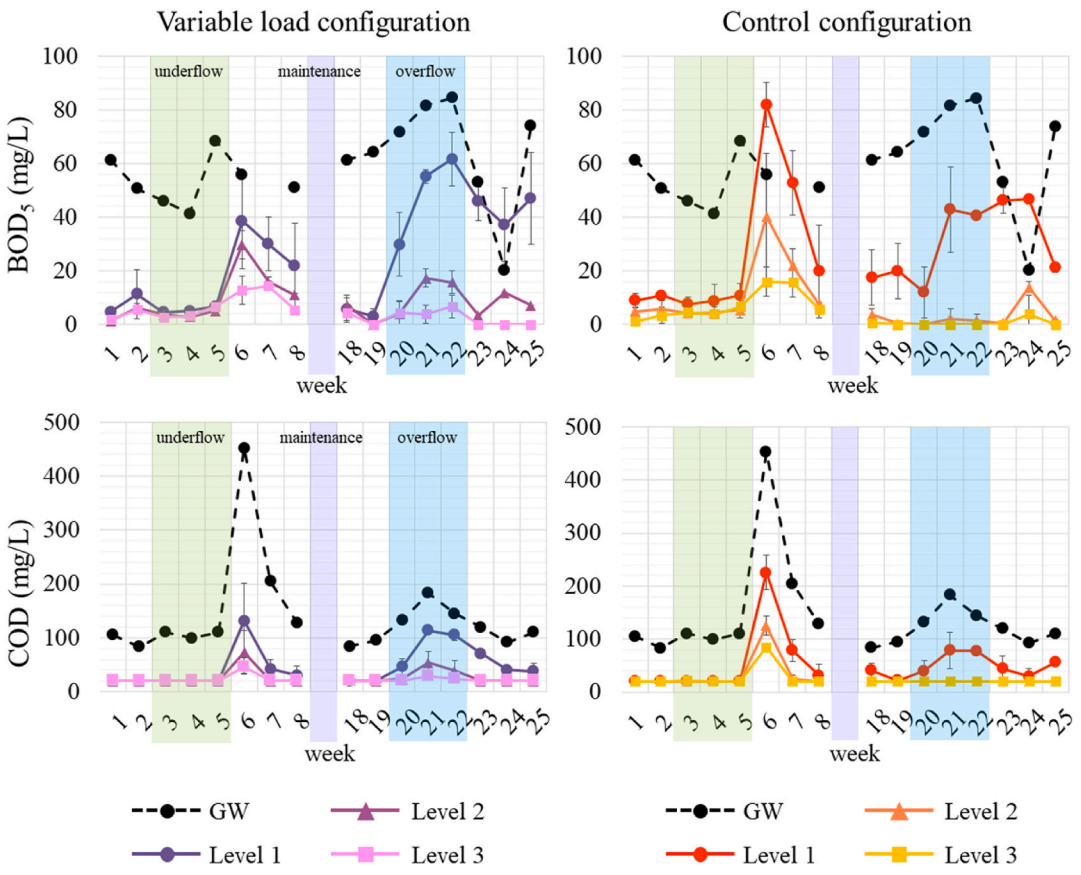

Fig. 6. Observed concentrations of BOD_5 and COD for the two tested configurations for input greywater (GW) and output samples from the three levels. For the variable load configuration, the green, purple and blue backgrounds denote the underload phase (weeks 3–5; HLR = 472 L m^{-2} day^{-1}), maintenance phase (weeks 9–17; HLR = 18 L m^{-2} day^{-1}) and overload phase (weeks 20–22; HLR = 1335 L m^{-2} day^{-1}). For the control configuration, the coloured backgrounds are reported for an easier visual comparison.

worsening of their conditions was observed.

3.3. Oxygen consumption rate and loading chart

To our knowledge, there is no published study on OCR values in green walls that is available for comparison. Therefore, the present results are compared with literature values reported for batch-fed vertical subsurface flow wetlands (VF) filled with coarse sand (0.2–2 mm), i.e., the treatment wetland solution which inspired the design of the green wall considered in the present study. The results are graphically represented in Fig. 9 and summarised in Table 2. No evid ent difference emerged from the comparison between the control configuration and the variable load configuration, confirming the high resilience of the tested green wall to hydraulic stresses. Interestingly, the first level (L1) exhibited a range of OCR (13–48 g_{O2} m^{-2} d^{-1}) in line with ranges reported for VF (30–60 g_{O2} m^{-2} d^{-1}; Nivala et al., 2013; Nivala et al., 2013), and the median values (around 30 g_{O2} m^{-2} d^{-1}) are in line with values recommended for designing VF (Dotro et al., 2017). These similarities indicate that the depth of the filter medium in a single pot (23 cm) was enough to transfer the same amount of oxygen considered for VF whose depth typically ranges between 0.80 and 1 m (Dotro et al., 2017). This finding agrees with modelling results (Morvannou et al., 2014) showing that most of the bacterial activity–and therefore aerobic biological removal– occurs in the shallowest (0.20–0.30 m) layer of VF. Compared to the typical behaviour of VF, the very efficient oxygen transfer found in this study could be due to different filter media (high porosity and permeability) or due to enhanced hydraulic functioning of the green wall. However, these performances should be further confirmed by long-term experiments as suggested by Pucher et al. (2022). Due to the high oxygen transfer of L1, the subsequent levels behave similarly to tertiary polishing stages with decreasing OCR (L2: 0.5–34 g_{O2} m^{-2} d^{-1}; L3: −0.8–9.5 g_{O2} m^{-2} d^{-1}). Therefore, if OCR is calculated using the whole surface area of all levels, the previous findings suggest that the design value of OCR should be lower (i.e., around 15 g_{O2} m^{-2} d^{-1}) than values used for VF (Fig. 9).

Despite the lower oxygen transfer, L2 and L3 played a relevant role in guaranteeing an effluent with BOD_5 concentration lower than 10 mg/L (i.e., the effluent standard set by the EU regulation 2020/741 for reuse in class A -unrestricted reuse). This is confirmed by the relationship between OLR and outflow BOD_5 concentration in Fig. 10, which shows that the excellent oxygen transfer of L1 already led to compliance with the limit $BOD_5 < 10$ mg/L in several cases. However, the presence of L2 and L3 increased the number of cases with $BOD_5 < 10$ mg/L to more than 90 % of the whole monitoring period. Fig. 10 also suggests that BOD_5 concentrations below 10 mg/L can only be guaranteed if the last treatment level receives an OLR lower than 20 g_{BOD5} m^{-2} d^{-1}. This threshold represents a valuable indication for future design guidelines.

Finally, caution should be used when areal values of OCR and OLR are employed for designing living walls for GW treatment. Indeed, the geometry of commercial modules for living walls can significantly depend on landscaping needs, wall structure or availability of local material. These differences in geometry lead to variations in the volume of filter medium per pot. For this reason, volumetric values of OCR and OLR and the corresponding loading charts were provided in the Supplementary Material (Table S-XIII, Fig. S–2).

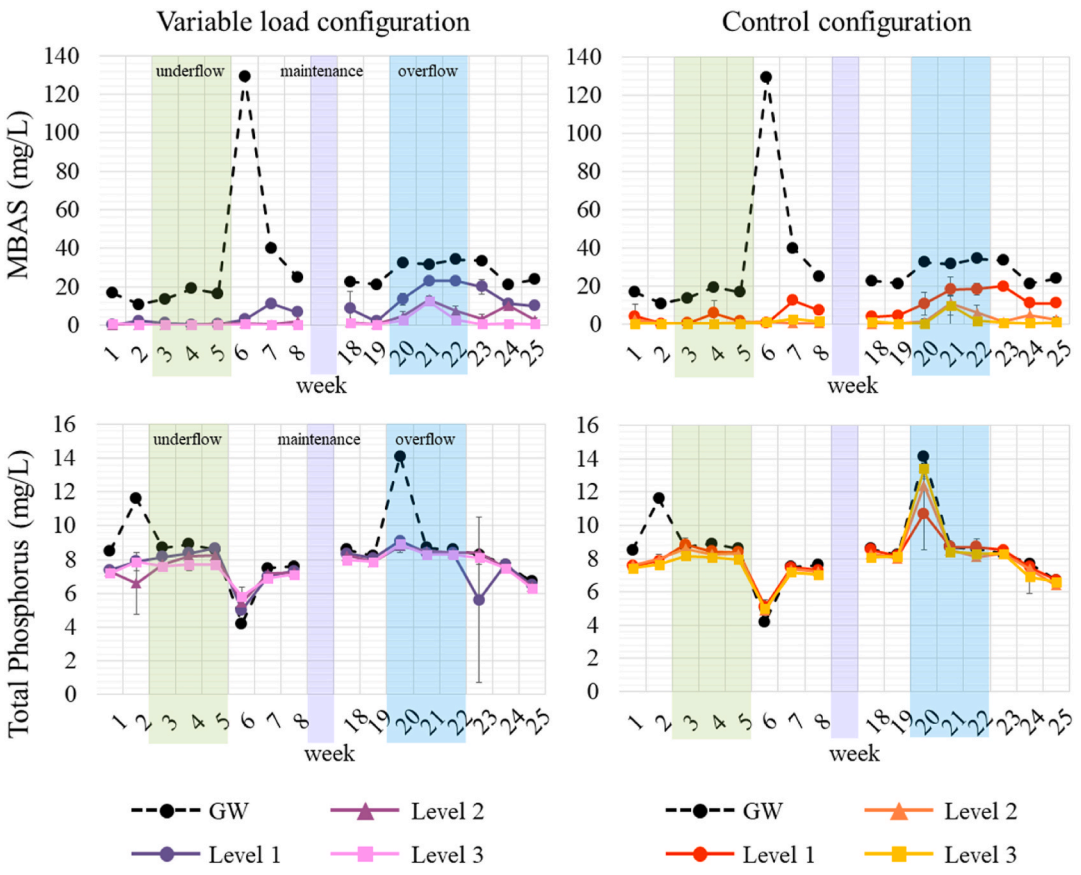

Fig. 7. Observed concentrations of MBAS and TP for the two tested configurations for input greywater (GW) and output samples from the three levels. For the variable load configuration, the green, purple and blue backgrounds denote the underload phase (weeks 3–5; HLR = 472 L m^{-2} day^{-1}), maintenance phase (weeks 9–17; HLR = 18 L m^{-2} day^{-1}) and overload phase (weeks 20–22; HLR = 1335 L m^{-2} day^{-1}). For the control configuration, the coloured backgrounds are reported for an easier visual comparison.

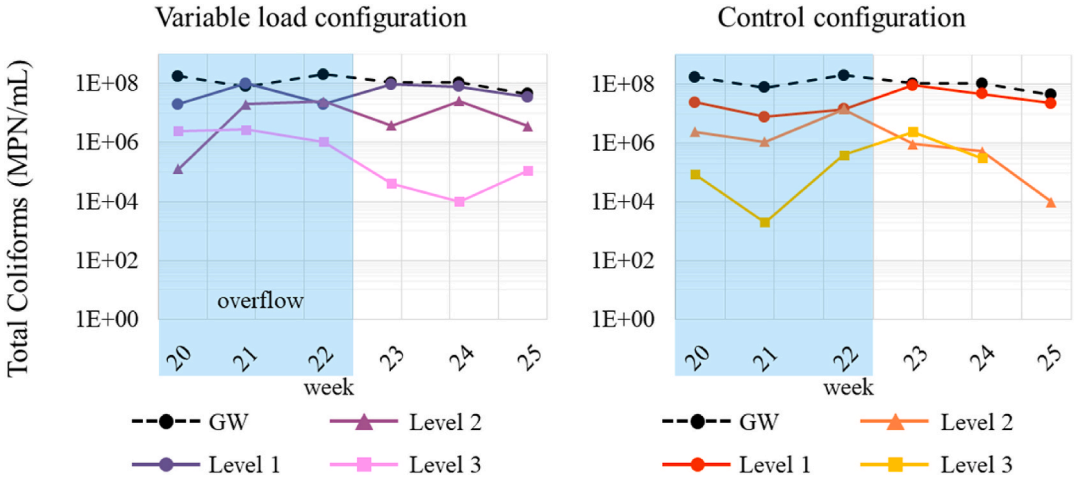

Fig. 8. Observed concentrations of Total Coliforms (TC) for the two tested configurations for input greywater (GW) and output samples from the three levels. For the variable load configuration, the blue background denotes the overload phase (weeks 20–22; HLR = 1335 L m^{-2} day^{-1}). For the control configuration, the coloured background is reported for an easier visual comparison.

3.4. Discussion on the overall treatment performance and implications for treated greywater reuse

Values of removal efficiencies and effluent concentrations from the present study are compared to literature results and international standards for reuse in Table 3. Despite t he significantly higher HLR tested in this study (470–1300 L m^{-2} d^{-1} on the first level; 150–450 L m^{-2} d^{-1} on the total treatment surface) in comparison to previous experiences (100–350 L m^{-2} d^{-1} on the first level; 10–100 L m^{-2} d^{-1} on the total treatment surface) with the same setup, the mean removal efficiencies were in line with values reported in the scientific literature for both the control configuration and the variable load configuration (Table 3). Except for some occasional effluent outliers, the treated GW met threshold concentrations for reuse in terms of TSS, BOD_5, COD, and TN

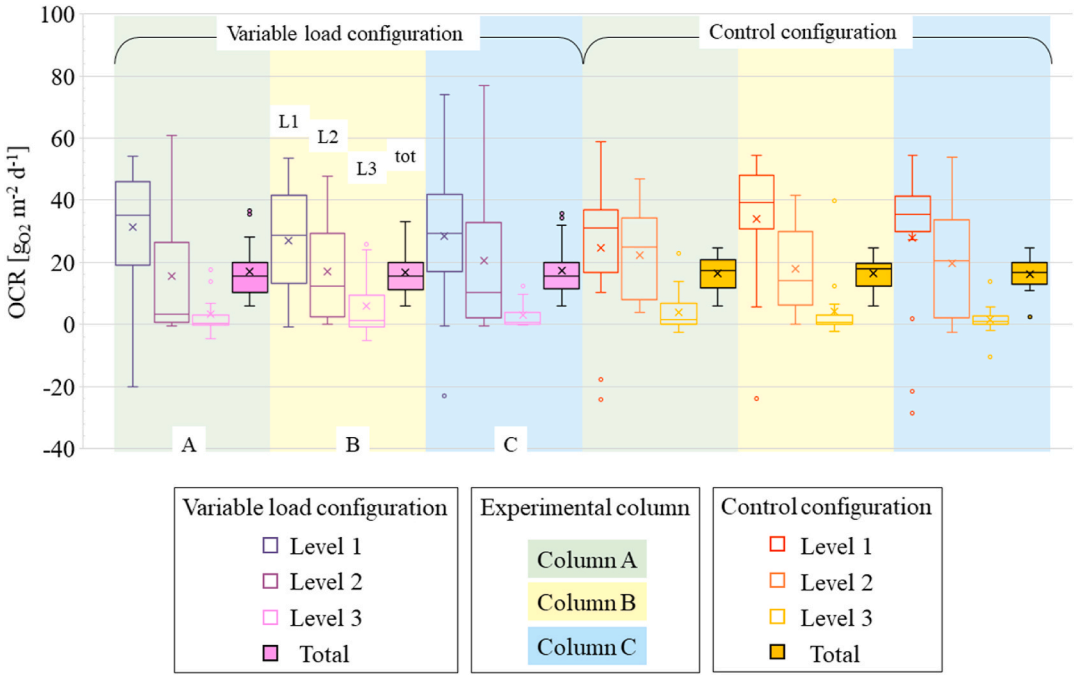

Fig. 9. Areal values of oxygen consumption rate (OCR) for each column of the control configuration and of the variable load configuration (A, B and C highlighted in different background colours denote the columns within each configuration). OCR values are reported for the single levels (from the darkest boxplot to the lightest) and for the whole columns (filled boxplot).

Table 2
Summary of the statistical analysis of the areal oxygen consumption rate (OCR) for each column of the control configuration and of the variable load configuration. OCR values are reported for the single levels and the whole columns (Median: average of the median values among the three replicates; Q1: minimum value of the first quartile among the three replicates; Q3: maximum value of the third quartile among the three replicates.

		Control configuration	Variable load configuration
		OCR [g_{O2} m^{-2} d^{-1}]	OCR [g_{O2} m^{-2} d^{-1}]
Level 1	Median	35	31
	Q1–Q3	17–48	13–46
Level 2	Median	19.8	8.7
	Q1–Q3	2.2–34	0.5–33
Level 3	Median	1.0	2.4
	Q1–Q3	0.0–6.7	−0.8–9.5
Total	Median	17	15
	Q1–Q3	12–20	10–20

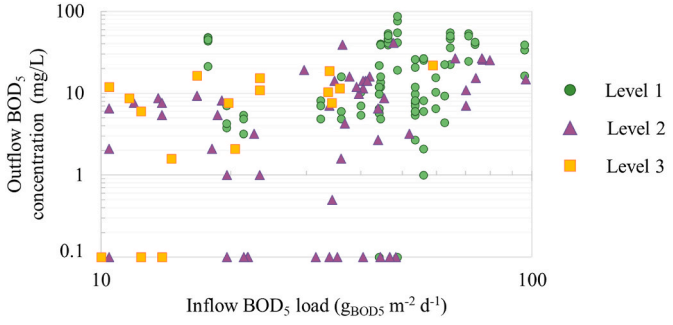

Fig. 10. Loading chart for areal values of BOD_5 for each column of the control configuration and of the variable load configuration.

(Table 3). However, in countries with strict effluent standards for MBAS (e.g., Italy, Slovenia, or China; <0.5–1.0 mg/L; Boano et al., 2020) the tested configurations would not achieve the target values, and further research is hence required to optimize the medium composition to fulfil stable concentrations below 0.5 mg/L for surfactants. For TP, our results at high HLR were at the low range of removal efficiencies reported in the literature; yet, different design setups should be adopted in countries with low TP required for reuse (e.g., Italy, Slovenia, or China with required standard 1.0–5.0 mg/L; Boano et al., 2020) as recently suggested by Gholami et al. (2023), considering also the use of alternative lightweight adsorbing materials (Vohla et al., 2011). Finally, despite the high removal efficiency of TC, green walls cannot be the only treatment stage for pathogens. Therefore, a disinfection unit is often recommended for the safe reuse of treated GW, similarly to other NbS as treatment wetlands (Arden and Ma, 2018).

4. Conclusions

The influence of temporal variations in the flow rate of GW fed to an outdoor green wall was investigated by considering four different HLR (i.e., standard, underload, maintenance, and overload) to reproduce variations in the building occupancy and thus in GW production. From a comparison between a variable load configuration and a control one with constant HLR, it was found that overload conditions led to a decrease in the removal efficiency of contaminants and generated stress for the plants of the green wall, while underload and maintenance had no negative influence on the system performances.

During underload conditions (50% less than standard HLR) the green wall handled the temporary reduction in the flow rate with no adverse effects on the performance of GW treatment or apparent damage to plant health. The same response was observed during the inflow reduction for maintenance conditions set for the holidays/summer period, showing stable results also when the standard load was restored and no visual damage to plants was observed. On the other hand, the overload condition (+50%) reproduced the case of increased occupancy of the building feeding the green wall. Results showed that this condition may slightly reduce the performance of GW treatment for some parameters (BOD_5 and COD). This decrease in treatment performance was particularly evident at the outflow of the first and second levels of pots, while the third level was able to partially compensate for the poorer efficiency

Table 3
Summary of treatment performance and effluent concentrations of the tested configurations with literature results and international standards for reuse. (a): mean values of cumulative removal efficiency at the third level (L3); (b): ranges refer to 1st quartile–3rd quartile of concentrations at the outflow of L3; (c): from (Bakheet et al., 2020; Boano et al., 2020, 2021a; Dal Ferro et al., 2021; Estelrich et al., 2021; Gattringer et al., 2016; Lakho et al., 2021, 2022; Masi et al., 2016; Prodanovic et al., 2019a, 2020; Pucher et al., 2022; Sami et al., 2023; Zraunig et al., 2019). HLR: first line 100–350 L m^{-2} d^{-1}; total treatment surface 10–100 L m^{-2} d^{-1}. Variable filter media (e.g. expanded clay, perlite, coco coir, organic soil, pumice, biochar); (d): from (Boano et al., 2020).

	Control configuration		Variable load configuration		Literature efficiencies[(c)]	International reuse standards[(d)]
	Removal efficiency[(a)]	Effluent concentration[(b)]	Removal efficiency[(a)]	Effluent concentration[(b)]		
TSS	>97 %	0.0–1.7 mg/L Max: 5.6 mg/L	>96 %	0.0–1.3 mg/L Max: 18.3 mg/L	50–95 %	10–200 mg/L
BOD_5	>93 %	0.0–5.7 mg/L Max: 21.9 mg/L	>91 %	0.0–7.6 mg/L Max: 18.6 mg/L	85–97 %	10–300 mg/L
COD	>82 %	<20 mg/L Max: 90.3 mg/L	>84 %	<20 mg/L Max: 56.0 mg/L	70–90 %	10–500 mg/L
MBAS	>93 %	0.20–1.67 mg/L Max: 14.9 mg/L	>94 %	0.27–1.89 mg/L Max: 12.8 mg/L	80–90 %	0.5–100 mg/L
TP	8 %	7.2–8.4 mg/L Max: 14.1 mg/L	10 %	7.1–8.3 mg/L Max: 9.4 mg/L	10–40 %	1–30 mg/L
TN	65–70 %	<5 mg/L Max: 2.2 mg/L	60–70 %	<5 mg/L Max: 2.6 mg/L	60–80 %	10–70 mg/L
TC	>99 %	$3.3\bullet10^4$–$2.5\bullet10^6$ MPN/100 mL Max: $2.7\bullet10^6$ MPN/100 mL	>99 %	$4.4\bullet10^4$–$1.4\bullet10^6$ MPN/100 mL Max: $2.4\bullet10^6$ MPN/100 mL	>70 %	0–10^3 MPN/100 mL

of the upper levels. The plants showed some degree of stress after two weeks of overload conditions, but they fully recovered when the standard flow was restored. These results indicate that the green wall may very well tolerate overload conditions for limited durations (e.g., a few days).

In terms of outlet water quality, the size of the green wall (here represented by the number of levels) played an important role to stabilize effluent concentrations and ensure BOD_5 concentrations suitable for reuse of treated GW. To comply with the EU regulation for unrestricted reuse of GW, values of inflow load of BOD_5 should be lower than 20 g_{BOD5} m^{-2} d^{-1} provided that the pot geometry is similar to the one adopted in this study. Furthermore, despite the excellent performance at high HLR, the proposed configuration still needs to be optimised to fulfil the strictest effluent standards for reuse in terms of surfactants and TP applied in some countries.

Finally, green walls for treatment of GW can be assimilated to batch-fed vertical subsurface flow wetlands, which have been employed for many decades. The quantitative comparison that has been performed here for the first time revealed very high values of oxygen consumption rates observed for the first level of the green wall. These values denote the high efficiency of oxygen transfer of the green wall compared with constructed wetlands. Because of this higher efficiency, design values of OCR for green walls for GW treatment should be lower than values used for constructed wetlands.

In conclusion, this study proved the robustness and resilience of a green wall exposed to outdoor temperatures between May and November in a temperate climate and stressed by significant variations of the hydraulic load fed to the system. The results can provide indications for design guidelines in this novel field, highlighting the importance of four main aspects: (i) selecting correctly the minimum system height (i.e., three levels, at least 20 cm each), (ii) considering the amount of GW to be treated according to the maximum occupancy of the building, (iii) set the GW feeding to provide enough time for oxygen transfer in the filter medium (i.e., pauses between flushes should be longer than the flush duration), (iv) selecting filter media with a proper hydraulic conductivity is important to reduce the risk of clogging and to enhance removal of contaminants. It should be noted that our design choice (one square meter of green wall per person equivalent) was aimed to test the performance of a relatively compact modular system. In actual applications, the alternative choice of adopting a lower GW flow rate per green wall surface would result in treatment performances that are higher than those shown in this study. It is also possible to treat only a fraction of greywater produced in a building, still providing some volume of reclaimed greywater for reuse and hence reducing the load on the centralized treatment plant.

CRediT authorship contribution statement

E. Costamagna: Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **A. Rizzo:** Writing – review & editing, Methodology, Conceptualization. **S. Fiore:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **F. Boano:** Writing – review & editing, Supervision, Project administration, 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.125114.

Data availability

Data will be made available on request.

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