



Evaluating a vertical greening system mesocosm for kitchen greywater treatment: Comparison among vegetation species in water consumption, biomass growth and pollutants uptake and removal

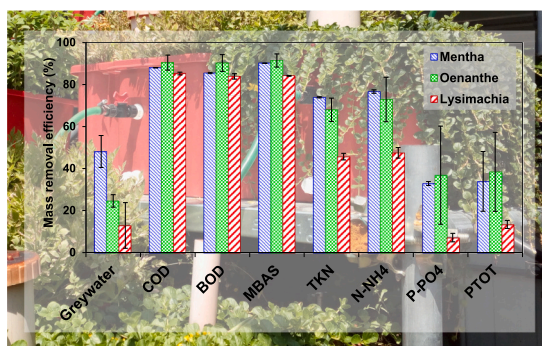
Nicola Dal Ferro^{*}, Nicola Celadon, Maurizio Borin

Department of Agronomy, Food, Natural Resources, Animals and Environment, University of Padova, Viale dell'Università 16, 35020 Legnaro, Padua, Italy

HIGHLIGHTS

- *Mentha* excelled in water removal efficiency compared to *Lysimachia* and *Oenanthe*.
- *Mentha* was less suitable if the recovery of treated water was an objective.
- *Mentha* more than doubled N (14 %) and P (7 %) removal compared to *Oenanthe* and *Lysimachia*
- Organic compounds were removed by >85 % from kitchen greywaters.

GRAPHICAL ABSTRACT



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ABSTRACT

The escalating climate imbalance, coupled with rising water demands in rapidly expanding urban areas, is forcing scientists and policymakers to seek alternative strategies for efficient water resource management. Nature Based Solutions (NBS) are gaining prominence due to their ability to provide multiple ecosystem services. However, the quantification of benefits and drawbacks mediated by different vegetation species remains inadequate. In this study, we investigated the performance of a pot-based vertical greening system (VGS) designed to integrate the functions of green facades with those of treatment wetlands. The VGS was vegetated with *Mentha aquatica* L. (hereafter *Mentha*), *Oenanthe javanica* (Blume) DC. (hereafter *Oenanthe*) and *Lysimachia nummularia* L. (hereafter *Lysimachia*), and their respective effects on water balance and mass removal of common greywater pollutants were compared. Results indicated that VGS lines vegetated with *Oenanthe* and *Mentha* exhibited comparable pollutant removals. *Oenanthe* showed a preference for greywater that had already undergone partial treatment, while *Mentha* was not affected by any pollutant load in water removal –48.1 % of total inflow– and in nutrients uptake in aboveground biomass –14.3 % N and 7 % P– due to sustained and robust growth, outperforming *Oenanthe* and *Lysimachia*. This has suggested the potential use of *Oenanthe* in combination with *Mentha* for enhanced performances, particularly given *Oenanthe*'s rapid growth in the early season and high biomass and nitrogen content following initial greywater treatment.

^{*} Corresponding author.

E-mail address: nicola.dalferro@unipd.it (N. Dal Ferro).

1. Introduction

According to the United Nations Department of Economic and Social Affairs (UNDESA, 2019), the percentage of the world's population living in cities is currently estimated between 55 and 60 %, with an increase to around 68 % in 2050. The growing global population is leading to increased challenges in urban water management, with critical issues including not only water supply but also wastewater management. With regard to the latter, attention has been put forth on the greywater decentralized treatment and recycling, which might achieve water savings of 9–46 % within the household (Boyjoo et al., 2013). Nature Based Solutions (NBS) are becoming increasingly sought-after as environmentally friendly, cost-effective solutions capable of enhancing the provision of multiple ecosystem services in rural areas (Toscano et al., 2013; Dal Ferro et al., 2019; Tolomio et al., 2019) and urban environments (Navarrete-Hernandez and Laffan, 2019; Dal Ferro et al., 2021; García-Herrero et al., 2022). The potentials of NBS in urban environments designed as natural wastewater treatments technologies have been widely demonstrated (Taylor et al., 2018; Cross et al., 2021), suggesting treatment wetlands (TWs) as an economically and energetically viable unit process to treat greywaters. In contrast, the feasibility of traditional TWs –whether vertical, horizontal, or hybrid– in densely populated urban areas has been impeded by their significant space requirements (Foladori et al., 2013; Ghosh and Gopal, 2010).

The challenge of implementing TWs in confined urban environments has pushed researchers toward multifunctional technologies (Castellar et al., 2022), where the benefits of vertically greening the buildings for temperature control, air filtering, etc. (Manso and Castro-Gomes, 2015) is combined with the capacity of treating wastewaters through TW systems (Castellar et al., 2018; Boano et al., 2021). This was achieved by implementing and testing, even in the long-term, vertical greening systems (VGS) that can be specifically identified as ground-based –climbing plants grow on the façade directly from the ground–, wall-based –plants grow in panels or textile structures integrated in the façade–, and pot-based –plants grow on boxes/pots which are attached to the facade or to a balcony– vegetated systems (Pucher et al., 2022). These systems can serve as treatment solutions by leveraging processes typically found in TWs (e.g., Zraunig et al., 2019; Boano et al., 2020).

Vertical greening systems are bound to become increasingly common in urban areas due to the delivery of multiple ecosystem services including aesthetic appearance and reduction of urban heat islands (Bustami et al., 2018; Stefanatou et al., 2023; Marín-Muñiz et al., 2024), compared to conventional infrastructures (Ascione et al., 2020; Manso et al., 2021). However, these systems are still far from being implemented on a large scale because a thorough quantification of multitude strengths and weaknesses including management aspects is not present yet. For example, interesting results about growing media solutions to be adopted for water treatment were reported by several authors, but these studies were generally conducted under strict controlled conditions (e.g. in the laboratory with synthetic greywater) (Prodanovic et al., 2018; Reyhani et al., 2023) or with specific climatic conditions on northern Europe (Sami et al., 2023). It follows that crucial plant-mediated effects on wastewater treatment, such as alterations in water balance or oxygen supply, particularly in temperate climates, have been rarely considered. Lakho et al. (2021) quantified the treatment performance of a full-scale VGS meeting suggested standards for toilet flushing, however organic growing media used as in traditional green walls had likely masked, e.g., knowledge of the self-sustained potential of wastewater-fed aquatic vegetation growth. In this context, the choice of vegetation species is pivotal, as it involves choosing plants on a combination of factors including, among others, modest growth to adapt to space-saving conditions and limited maintenance, tolerance to high levels of contamination, and aesthetic value (Addo-Bankas et al., 2021).

In a previous study we have evaluated the treatment performance of a pilot scale pot-based terraced VGS treating kitchen greywater under real-world conditions (Dal Ferro et al., 2021), demonstrating the ability

of the system to reduce the concentrations of organic pollutants (> 80 % for COD, BOD₅, MBAS) and nitrogen (>55 % for TKN) in a two-year experiment. Although these results were encouraging and useful to assess the suitability of the treated waters to be discharged or reused according to local regulations, they express only first estimates of the potential of a class of TWs to reduce the contaminants (Kadlec and Wallace, 2009). A much better characterization of the performance is achieved by computing mass removal and mass balance, because they link water losses and gains to chemical losses and gains. Their calculations require both measurements of water flows and concentrations within those waters. Therefore, an accurate water mass balance is a prerequisite to an accurate chemical mass balance. Furthermore, the factors associated with biomass growth, nutrients uptake in biomass and water balance are pivotal for addressing various management aspects, e.g. biomass management and removal and the amount of water that can be recovered and reused. These considerations are crucial for the development of effective green infrastructure. In this context, the present paper has the aims of: i) estimating the mass removal potential of water and pollutants by the green wall; ii) testing and identifying most suitable vegetation species to remove pollutants and regulate the water balance.

2. Material and methods

2.1. Experimental setup

The tested VGS was a pot-based (Langergraber et al., 2021) terraced green façade built and placed at the “Agripolis” Campus of the University of Padova in the municipality of Legnaro (8 m a.s.l., 45°21'N 11°58'E, Padova province in northeastern Italy) in May 2017. It was a pilot-scale VGS operating under real-world conditions regarding greywater quality and sizing of unit elements to support vegetation (Fig. 1).

The pot-based VGS was formed by a terraced structure to embed six different greywater treatment lines, occupying a total area of 16.4 m². Each line was made up of three in-series vegetation PVC unit elements (0.35 × 0.45 × 0.27 m) at increasing heights (upper, medium, and lower levels) connected by HDPE pipes, through which the effluent to be treated flowed vertically by gravity. At the end of the treatment, the effluent accumulated in water containers, one for each line, before being transferred to the laboratory for freeze-storage and subsequent analyses.

A batch management approach for greywater input was maintained throughout the experiment. The entering greywater forced the greywater already present inside a treatment unit to pass through the substrate, and then to rise along a tube to exit and fall in the lower unit. The water level in each unit decreased due to plant evapotranspiration (especially in the summer period), allowing air to be drawn in between the daily feeding cycles that favoured alternation between anaerobic and aerobic conditions (Dal Ferro et al., 2021). A 1-m³ container was used to store the greywater before input. From that, a submerged hydraulic pump was used to transfer the greywater into six feeding drums, one for each treatment line.

Three species (Table 1) were used to vegetate each unit element of the treatment lines, previously filled with light expanded clay aggregates (LECA®; total porosity = 0.55 m³ m⁻³; particle size = 10–20 mm): *Mentha aquatica* L. –hereafter called Mentha– *Oenanthe javanica* (Blume) DC. –hereafter called Oenanthe– and *Lysimachia nummularia* L. –hereafter called Lysimachia. The six treatment lines were vegetated with one plant species each (6 plants per unit element), so that they were replicated twice. These plant species were chosen for their ability to adapt to the conditions of the plant system (reduced spaces with saturation-unsaturation alternation), for their resistance to contaminated water, and aesthetic reasons. These species were all perennials and rhizomatous.

2.2. System management and monitoring

Real kitchen greywater from the university canteen was used throughout the experiment. The produced greywater came from the preparation of meals comprising the entire process: from the washing of fruit and vegetables to the cooking waters and dishwashing. Greywater was regularly collected from the dedicated septic tank that was used for primary anaerobic digestion, sedimentation, and grease trap before being transferred to a conventional sewage treatment.

At the beginning of the trial six rooted plants, about 10 cm height, were transplanted on each unit element. For approximately one week, they were watered only using tap water and then, gradually, an increasing amount of greywater was mixed to the point when, 15 days after the start of the trial, only greywater was used. The experimentation lasted almost 2 years, from June 2017 to April 2019. During the winter period, the VGS was covered with a greenhouse plastic film to prolong the vegetation growing season. The experimental trial was divided into four seasonal monitoring periods (Table 1), corresponding to the data collected during: 14/06/17–04/08/17 (hereafter called Summer 2017); 06/10/17–28/03/18 (hereafter called Winter 2017); 28/03/18–14/09/18 (hereafter called Summer 2018); 09/10/18–14/04/19 (hereafter called Winter 2018). During the experiment, a meteorological station nearby was used to monitor air temperature and rainfall that was also used to correct the inflow volumes, and to estimate the reference evapotranspiration (ET_0) according to Hargreaves equation (Berti et al., 2014). Considering the entire period, an average daily temperature of 15.3 ± 0.3 °C was recorded, with an average daily minimum of 0.5 °C and a maximum of 30.6 °C (Table 2).

The main physicochemical parameters concerning water quality (pH; electrical conductivity–EC, $\mu\text{S cm}^{-1}$; T, °C; dissolved oxygen–DO, mg L^{-1}) were monitored throughout the experiment in the inflow, outflow, and in each unit element at an average frequency of 15 days. In-situ measurements were taken using a HQ40D portable multi-parameter meter (Hach, Loveland, CO). Water turbidity, expressed in

Table 1

Set-up and operation parameters for the 2-year experiment.

Parameter	Value	Description
Dimension of the TW system (m^2)	2.84	
Total testing period	June 2017–April 2019	
Loading intervals	14/06/2017–04/08/2017 (51 days)	Summer 2017
	06/10/2017–28/03/2018 (173 days)	Winter 2017
	29/03/2018–14/09/2018 (169 days)	Summer 2018
	09/10/2018–14/04/2019 (191 days)	Winter 2018
Hydraulic loading rate ($\text{L m}^{-2} \text{d}^{-1}$)	15.7	Summer 2017
	4.4	Winter 2017
	24.5	Summer 2018
	9.3	Winter 2018
Organic loading rate ($\text{g COD m}^{-2} \text{d}^{-1}$)	11.0	Summer 2017
	3.4	Winter 2017
	16.5	Summer 2018
	10.1	Winter 2018
Plant growing medium	Leca®, particle size = 10–20 mm	Expanded clay aggregates
Plants used and harvesting	<i>Mentha aquatica</i> L. <i>Oenanthe javanica</i> (Blume) DC. <i>Lysimachia nummularia</i> L.	Total harvesting was done on only for monitoring purposes at the end of the experiment.

nephelometric turbidity units (NTU) was measured with a 2100P portable turbidity meter (Hach, Loveland, CO). Organic compounds (COD; BOD₅, mg L^{-1}), MBAS (mg L^{-1}), and nutrients (ammonium nitrogen–N-NH₄; nitrate nitrogen–N-NO₃; Kjeldahl nitrogen–TKN; total phosphorus and orthophosphate–P_{tot}, P-PO₄, mg L^{-1}) were measured in incoming and outgoing effluents at an average frequency of 15 days. The

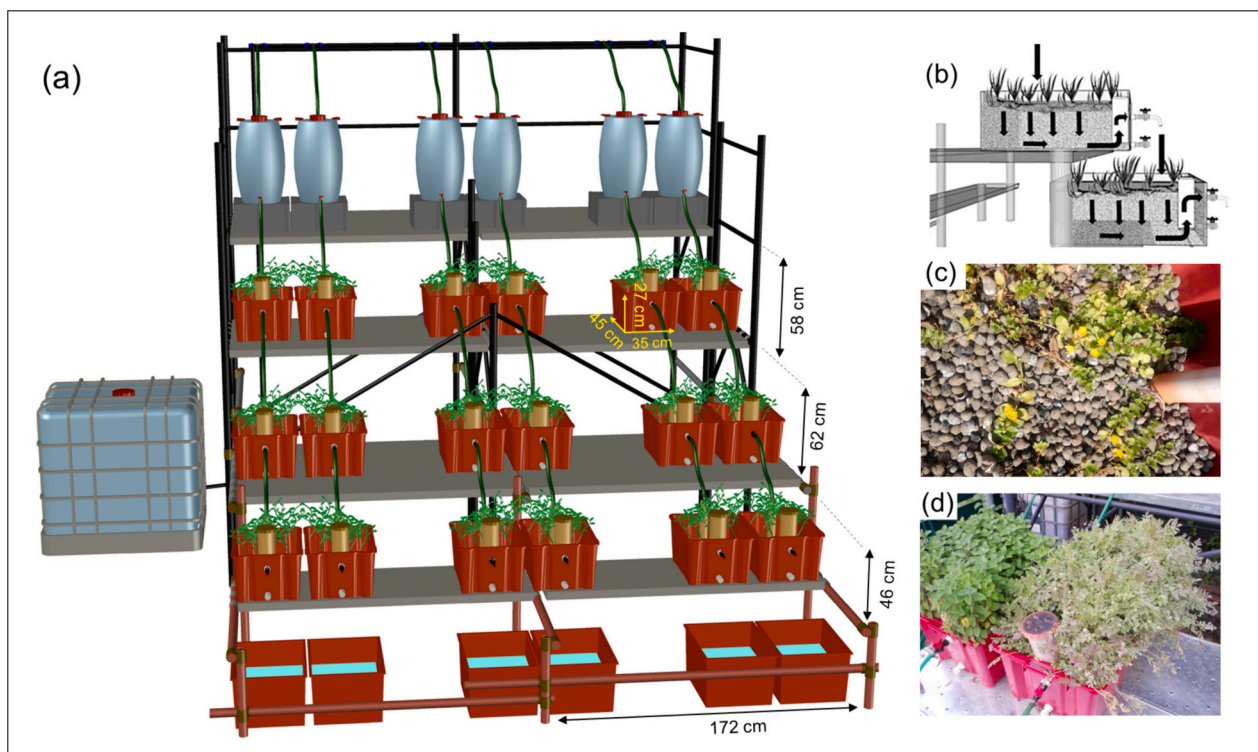


Fig. 1. Sketch of the pot-based VGS (a), inflow-outflow greywater dynamics (b), and pictures of the operational VGS with details about LECA® (c) and vegetation (d). A 1-m³ accumulation tank was used to store the kitchen greywater (a). A submersible hydraulic pump was used to transfer the greywater into the feeding drums, one for each vegetated line, each of which had three treatment units in series.

Table 2
Average weather conditions during the 2-year experiment.

Experiment period	Temperature (°C)			Rainfall (mm d ⁻¹)	ET ₀ (mm d ⁻¹)
	Average	Min	Max		
Summer 2017	24.7	12.7	37.0	1.8	5.5
Winter 2017	6.8	-6.0	24.7	2.0	1.1
Summer 2018	21.5	0.7	36.1	2.5	4.5
Winter 2018	8.3	-5.5	24.7	1.5	1.3

collected water was immediately transferred to the laboratory and stored refrigerated prior to performing the specific chemical analyses. The N-NH₄, N-NO₃ and P-PO₄ were determined by ion chromatography (Nicoletto et al., 2019), while TKN was determined according to Latimer (2012). The COD and MBAS were measured with a spectrophotometer (Hach, Loveland, CO) using the LCK 314 COD method (measuring range 15–150 mg L⁻¹) or LCK 514 COD (100–2000 mg L⁻¹), and LCK 432 MBAS (measuring range 0.1–4.0 mg L⁻¹) in cuvettes, depending on the concentration to be measured (Dimitrova et al., 2013). The BOD₅ was measured using the respirometric BOD OxiTop® method (WTW, Xylem Analytics, D) based on an accurate pressure measurement (Vähäoja et al., 2005). The main physicochemical properties and chemical concentrations of the monitored pollutants in the inflow and outflow greywater were already reported in Dal Ferro et al. (2021), and here summarized (details in supplementary Table S1, S2). Regarding the inflow (Table S1), average temperatures were significantly higher in summer 2017 (26.5 °C) than 2018 (20.8 °C) monitoring periods and decreased down to 11.3 and 9.3 °C in winter 2018 and 2017 (not significant). The pH was generally higher than 8.0, apart for summer 2018 when the pH averaged 7.2. The electrical conductivity of the inflow greywater was always >1000 μS cm⁻¹, with statistical differences that did not depend on summer-winter temperature seasonality. Regarding the main chemical pollutants, statistical differences were only observed in terms of N-NH₄ and N-NO₃, while the organic pollutants as well as P were fairly uniform throughout the 2-year monitoring period (supplementary Table S1).

2.3. Vegetation sampling and analysis

The investigation of vegetation entailed assessing growth dynamics in relation to aboveground biomass through sampling conducted during the experiment. The sampling of plant material covered a portion of each unit element, comprising a 0.02 m²-area (0.1 m × 0.2 m) representing 12.3 % of the total surface of each unit element. The harvesting was done four times in 2018 with a three-fold harvesting during the growing season (28/03/2018, 25/05/2018, 20/07/2018) and an additional sampling that was conducted just before dormancy (10/09/2018), each time in previously unsampled areas. The vegetation samples were immediately weighed to determine the fresh weight, thereafter oven-dried at 65 °C until constant weight for determining the dry biomass. Finally, the vegetation was ground with a mill and transferred to the laboratory for determining N and P content.

2.4. Water volumes and removal of nutrients and organic compounds monitoring

Throughout the 2-year experiment, all inflow and outflow greywater events were recorded. Inflow (V_{In} , L m⁻²) was the greywater volume entering the green wall CW from the feeding drums (before the first unit element) plus rainfall (R), while outflow (V_{Out} , L m⁻²) was the treated effluent exiting into the water containers (after the last -third- unit element), per monitoring season.

The mass of nutrients and organic compounds entering the VGS was calculated in each monitoring season. The mass at the inlet (M_{In} , g m⁻²) was calculated as the product of pollutants concentration (mg L⁻¹) in the inlet and the water inflow; that at the outlet was calculated (M_{Out} , g

m⁻²) as the product of the pollutant's concentration in the outlet and the water outflow. Since nutrients and organic compound concentrations were monitored at a lower frequency (on average, every 15 days) than actual inflow and outflow events, masses between measurements were estimated according to the trapezoidal rule as follows (Lord and Shepherd, 1993):

$$M_k = \frac{0.5 \cdot (C1_k + c2_k) \cdot V}{1000}, \quad (1)$$

where M_k is the k -th mass of the pollutant (g m⁻²) in the inflow (or outflow), $c1_k$ and $c2_k$ are the measured concentrations of the pollutant in two consequent time intervals, V is the inflow (or outflow) water volume (L m⁻²) between the two-time intervals. Subsequently, the M_k -th values were summed into cumulative values referable to each seasonal monitoring period and the entire 2-year experiment. The N and P nutrients in the aboveground vegetation were also quantified in terms of mass ($M_{Veg(k)}$) as the product between the k -th concentration ($C_{Veg(k)}$, g g⁻¹) and the dry biomass (M_{Veg} , g m⁻²) at the end of the growing season corresponding to the last harvesting:

$$M_{Veg(k)} = C_{Veg(k)} \cdot M_{Veg} \quad (2)$$

where total N and P concentrations (g g⁻¹) were determined in the laboratory through Kjeldhal method (Kjeltec 2300 Auto Analyser; Foss-Tecator, Hillerød, Denmark) and ICP-OES (Arcos EOP, Spectro A.I. GmbH, Kleve, Germany) (Zanin et al., 2020) methods, respectively.

2.5. Data analysis

The water balance method was used to compare the contribution of vegetation species to modify the water management within the VGS. All recorded volumes about inflow (V_{In} , R) and outflow (V_{Out}) were used to estimate the actual evapotranspiration (ET) within each vegetated line on a daily basis:

$$ET = V_{In} + R - V_{Out} \quad (3)$$

The VGS treatment performance in every seasonal monitoring period and across the 2-year experiment was evaluated for nutrients or organic compounds in terms of net mass removal:

$$M_{Net(k)} = M_{In(k)} - M_{Out(k)}, \quad (4)$$

and in terms of percentage mass removal:

$$M_{\% (k)} = \frac{M_{In(k)} - M_{Out(k)}}{M_{In(k)}} \cdot 100. \quad (5)$$

Moreover, the average daily removals in terms of both evapotranspiration and mass were evaluated for each seasonal monitoring period.

Fresh and dry biomass were analysed through a repeated factors (time of sampling) ANOVA with vegetation species (*Mentha*, *Lysimachia*, *Oenanthe*) and vegetation position along the green wall (upper, medium and lower level) as treatment factors. The total water outflow volumes (V_{Out}), the cumulative outflow pollutants (COD, BOD₅, MBAS, TKN, N-NH₄, N-NO₃, P-PO₄, P_{tot}), as well as the water and mass pollutant values measured during the four monitoring seasons were analysed with a one-way ANOVA, where vegetation species was the treatment factor under investigation. Moreover, N and P concentration and uptake in aboveground vegetation at harvest was analysed with a one-way ANOVA, where vegetation species were the treatments. Significantly different means were differentiated with the Tukey HSD test ($p < 0.05$). Finally, Pearson's correlation coefficients were used to find possible linear relationships ($p < 0.05$) between percent removal of water and pollutants with respect to seasonality, evaluated in terms of effluent temperature. Statistical analyses were performed with STATISTICA version 10.0 (Statsoft Inc., USA).

3. Results and discussion

3.1. Vegetation growth dynamics

The fresh biomass of all vegetation species generally increased from March to May, and afterwards it slightly decreased until the sampling that was conducted in July across all the vegetation positions (Table 3). Different growth dynamics between vegetation species were observed from July to September, when the fresh biomass had in some positions new vigour in both *Lysimachia* (upper level, from 874 to 1077 g m⁻²) and *Mentha* (upper and medium levels, from 6030 to 8760 g m⁻², on average), while a sharp decrease was observed in *Oenanthe* suggesting its early decay phase (Zhou and Wang, 2010) compared to the others. The statistical analysis showed that most of the differences in fresh biomass were found between *Lysimachia* and both *Mentha* and *Oenanthe*, highlighting that *Lysimachia* produced relatively less biomass compared to the other two plant species across the monitoring sampling season (Supplementary Table S3, S4). Even the vegetation position within the pot-based terraced VGS influenced the growth, with *Mentha* that showed its ability to grow more ($p < 0.05$) than the others especially in the upper level (7337, 1043, 2282 g m⁻² in *Mentha*, *Lysimachia* and *Oenanthe*, respectively) (Table 3), i.e. under conditions of highest water contamination (Supplementary Table S5), that thereafter diminished due to the greywater treatment process (Dal Ferro et al., 2021). These results corroborate previous findings, when it was found that greywater electrical conductivity through the pot-based VGS levels increased especially in *Mentha*, most likely due to its fast growing and its evapotranspiration-induced effect on salt concentration (Dal Ferro et al., 2021). The highest fresh weight, in the intermediate level, was generally found with *Oenanthe*, apart from the last sampling date when *Mentha* showed significant higher values due to decay of the *Oenanthe* plants (Supplementary Table S5). *Lysimachia* most suffered from greywater contamination, being the upper level of the VGS usually showing significantly lower biomass (1043.5 g m⁻²) than the medium (2175.8 g m⁻²) and lower levels (2175.3 g m⁻²) (Supplementary Table S5). Moreover, it proved to colonise slowly the available environment corroborating previous findings (Cossu et al., 2003), thus maximising the risk of medium colonisation by weeds with negative consequences in terms of greywater treatment performance and green

wall management. The dry biomass showed similar dynamics compared to fresh biomass (Table 3), with most of the significant differences that were found between species, both interacting with growth dynamics (time of sampling) and with vegetation position in the VGS (Supplementary Table S3). *Mentha* showed comparable biomass production in the upper level (2810 g m⁻²) with the findings from previous studies (Barco and Borin, 2020), where *Mentha* reached a biomass up to 3162 g m⁻² in vegetated floating systems under optimal spiked nutrient solution conditions. Such findings were lower than those found by Avellán and Gremillion (2019) when vegetation biomass from TW plants were compared, being the average dry biomass of 3276 g m⁻². However, our results can still be considered high, since the species being compared were macrophytes characterised by high vegetative development such as *Phragmites* spp., *Typha* spp., *C. papyrus* and *A. donax*. These findings imply that *Mentha* exhibited an adaptive capability to thrive in wastewater environments rich in nutrients (Sangeetha et al., 2023), in contrast to conditions found in other real-world settings such as stormwater management in bioretention ponds (Zanin et al., 2018). In those environments, nutrient levels are usually significantly lower (on average NO₃ < 1 mg L⁻¹; PO₄ = 1.22 mg L⁻¹) compared to our study condition (Supplementary Table S2), potentially constraining vegetation growth.

It is noteworthy that even in terms of dry biomass, a significant reduction was observed in *Oenanthe* between July and September. This suggests that decay was accompanied by tissue detachment and loss in the environment, as the experiment was conducted outdoors under real conditions and subjected to meteorological events such as rain and wind. Additionally, relatively high temperatures likely contributed to early dead biomass mineralization (Table 2). In contrast, such behaviour would not suggest that *Oenanthe* suffered from biomass growth inhibition due to greywater use, being the adaptability to TWs of this specific species already tested (Barco and Borin, 2020; Hu et al., 2010), as well as the produced biomass aligned with the best growing performance that was reported in other studies (max 808 g m⁻² d.m.) (Zhou and Wang, 2010).

Biomass growth alone may not be a sufficient indicator to determine the suitability of *Oenanthe* or the other tested species for greywater treatment. Biomass is not always correlated with key plant vitality parameters, such as health, vigour, and growth rate, which are essential for

Table 3

Average vales (±standard error) of fresh and dry biomass (g m⁻²) of the three vegetation species in the four harvest periods, divided into the different positions.

Plant species	In-series vegetation position	28/03/2018		25/05/2018		20/07/2018		10/09/2018	
		Fresh biomass g m ⁻²	Dry biomass g m ⁻²	Fresh biomass g m ⁻²	Dry biomass g m ⁻²	Fresh biomass g m ⁻²	Dry biomass g m ⁻²	Fresh biomass g m ⁻²	Dry biomass g m ⁻²
<i>Mentha</i>	Upper level	1271.6 ± 479.5	149.8 ± 53.8	8552.3 ± 1018.3	1269.5 ± 233.5	7389.0 ± 370.5	1591.8 ± 98.8	12,138.8 ± 3614.8	2810.3 ± 881.3
	Medium level	719.9 ± 244.9	99.0 ± 18.5	5836.8 ± 1133.3	910.5 ± 215.5	4672.0 ± 1246.0	978.8 ± 291.8	5382.8 ± 1292.3	1197.5 ± 347.5
	Lower level	341.3 ± 127.8	50.2 ± 17.2	3373.3 ± 746.8	492.3 ± 108.8	4016.8 ± 557.3	940.8 ± 144.8	2356.0 ± 180.0	529.5 ± 45.5
	Average	777.6 ± 222.7	99.7 ± 23.8	5920.8 ± 1042.4	890.8 ± 166.4	5359.3 ± 748.1	1170.4 ± 159.8	6625.8 ± 2080.7	1512.4 ± 493.2
<i>Oenanthe</i>	Upper level	1290.9 ± 338.2	147.7 ± 40.3	5238.5 ± 1910.5	747.0 ± 266.0	1927.5 ± 574.0	298.8 ± 126.3	674.0 ± 200.0	90.0 ± 34.0
	Medium level	4132.3 ± 1112.3	527.0 ± 119.0	11,222.0 ± 248.0	1419.8 ± 207.3	9731.0 ± 1237.0	1430.0 ± 208.0	2657.3 ± 407.3	259.0 ± 20.0
	Lower level	1848.6 ± 161.7	275.7 ± 4.3	9321.3 ± 1751.8	1022.3 ± 255.8	8583.5 ± 992.0	1343.8 ± 121.8	4569.5 ± 191.5	430.5 ± 51.5
	Average	2423.8 ± 627.8	316.8 ± 77.6	8593.9 ± 1303.2	1063.0 ± 164.9	6747.3 ± 1598.9	1024.2 ± 240.4	2633.6 ± 722.5	259.8 ± 64.4
<i>Lysimachia</i>	Upper level	935.6 ± 492.5	230.3 ± 134.3	1287.3 ± 497.8	317.0 ± 123.0	874.5 ± 874.5	181.8 ± 181.8	1077.8 ± 1077.8	406.5 ± n.a.
	Medium level	1939.4 ± 224.1	365.8 ± 32.3	3046.5 ± 256.0	660.0 ± 32.5	2545.0 ± 23.5	553.3 ± 79.8	1173.3 ± 1173.3	412.5 ± n.a.
	Lower level	752.5 ± 89.9	196.8 ± 23.8	3345.3 ± 829.3	765.3 ± 167.8	2336.8 ± 210.8	626.8 ± 63.8	2268.8 ± 975.3	476.8 ± 170.8
	Average	1209.2 ± 272.9	264.3 ± 48.8	2559.7 ± 481.3	580.8 ± 101.4	1918.8 ± 405.6	453.9 ± 102.4	1506.6 ± 539.4	443.1 ± 56.1

assessing plant suitability for TWs. However, most of the literature suggests the potential for using greywater in VGS. For instance, Pucher et al. (2022) tested different irrigation intervals and water volumes in a pot-based VGS over 16 months, monitoring 39 plant species under tap water and untreated synthetic greywater. They reported similar vitality and biomass across most of the species, suggesting the system's feasibility after two vegetation periods. Similarly, Chung et al. (2021) studied the growth of six climbing plant species for a green façade under tap water and greywater irrigation, finding no significant differences in plant growth and gas exchange rates. In this context, our results further support the findings of the literature, especially considering that the greywater tested in our study was of lower quality than that reported in many other studies.

3.2. Water dynamics and water balance

The same greywater volume was supplied to all vegetated lines of the VGS all along the experiment, which totally amounted 7478.5 L m⁻², of which the majority was provided during summer 2018 (4136.7 L m⁻²) (Table 4). The same rainfall amount contributed to feed all vegetated lines with 7.4 % of total input volume. Most of the rainfall occurred in 2018 experimental season, because little events were observed during the 51 days of summer 2017 monitoring, and in winter 2017 a plastic film covered the VGS as a greenhouse for the entire period. The estimated hydraulic loading rates, including rainfall, varied in the different monitoring seasons with values in the 2017 of 17.4 and 4.4 L m⁻² d⁻¹ in summer and winter that increased of +35 % and + 55 % during 2018, respectively.

Cumulated outflow volumes during the two-year experiment changed according to the vegetation system (Table 4), with values that significantly increased from Mentha (TOT-V_{Out} = 3880.7 L m⁻²) to Oenanthe (TOT-V_{Out} = 5636.6 L m⁻²) and finally to Lysimachia (TOT-V_{Out} = 6511.7 L m⁻²). Comparing to total input, the water consumption by vegetation species (estimated actual ET) was almost doubled from Lysimachia (12.9 %) to Oenanthe (24.6 %) and finally to Mentha (48.1 %) (Fig. 2), suggesting that certain plant species may be more effective than others in reducing treated greywater discharge volumes. Additionally, selecting a particular species may require estimating input volumes and appropriately sizing the VGS to prevent water stress. This is especially important for small vertical surfaces exposed to high summer temperatures, where the risk of water stress that could compromise plant health is heightened (Pucher et al., 2022), thus limiting the potentials for mitigating urban heating islands through evapotranspiration and local cooling (Cheng et al., 2010; Gräf et al., 2021). Similar water consumption rates were found by Tamiazzo et al. (2015) in a pot-based terraced green façade used as a treatment wetland for treating car washing wastewaters under similar conditions of retention time (3–6 days), being estimated ET in between 35 % and 44 %. Plant seasonality contributed to modify the water outflow (Fig. 3), with similar dynamics in the retention among vegetation species during the winter periods when dormancy mainly occurred, especially in 2017 (ET in the range of 125.7–225 L m⁻², 0.73–1.3 L m⁻² d⁻¹; 416.2–815.4 L m⁻², 2.18–4.46 L m⁻² d⁻¹ in winter season 2017 and 2018, respectively), and increased outflow gaps during the summer (range of 198.2–491.4 L m⁻² and 746.9–2559.1 L m⁻² in 2017 and 2018, respectively) (Fig. 3, Table 4). This dynamic was highlighted by the significant relations that were observed through the 2-year experiment and reported in Fig. 4, where the greywater removal increased at increasing greywater temperatures. Regardless these significant relationships, it is noteworthy that greywater removal differed among species, highlighting the greater evapotranspiration capacity of Mentha with more pronounced vegetative development compared to Oenanthe and Lysimachia.

The estimation of daily retained water, which is useful for understanding water requirements as well the effects of plants and climate, revealed that the VGS held on average 0.9 L m⁻² d⁻¹ (daily estimated ET) during winter 2017 across all vegetated lines, that increased up to

Table 4 Greywater cumulative (L m⁻²) and daily (L m⁻² d⁻¹) inflow (V_{In}, Rainfall) and outflow (V_{Out}) volumes measured in the VGS, and estimated evapotranspiration (ET). Values of V_{Out} labelled with different letters were significant at p < 0.05 (Tukey HSD test).

	Inflow			Outflow Mentha			Outflow Oenanthe			Outflow Lysimachia					
	V _{In} L m ⁻²	Rainfall L m ⁻²	TOT-V _{In} L m ⁻²	V _{Out} L m ⁻²	ET L m ⁻²	V _{Out} L m ⁻²	ET L m ⁻²	V _{Out} L m ⁻²	ET L m ⁻²	V _{Out} L m ⁻²	ET L m ⁻²				
Summer 2017	804.2	84.4	888.6	17.42	6.13	312.8 ^b ± 0.8	11.29	575.8 ± 0.8	10.74	341.0 ± 0.7	6.69	606.0 ^a ± 0.7	11.88	282.6 ± 0.7	5.54
Winter 2017	759.8	0.0	759.8	4.39	3.09	534.6 ^b ± 0.9	1.30	225.2 ± 0.8	3.35	180.2 ± 0.5	1.04	634.1 ^a ± 0.6	3.67	125.7 ± 0.5	0.73
Summer 2018	4136.7	399.7	4536.4	26.84	11.75	1986.3 ^b ± 1.4	15.09	2550.1 ± 1.2	18.46	1416.7 ± 0.9	8.38	3789.5 ^a ± 1.0	22.42	746.9 ± 0.6	4.42
Winter 2018	1777.8	120.6	1898.4	9.94	5.48	1047.0 ^b ± 1.5	4.46	851.4 ± 1.6	7.28	508.7 ± 1.5	2.66	1482.2 ^a ± 1.1	7.76	416.2 ± 1.5	2.18
Total/Average	7478.5	604.7	8083.2	13.84	6.65	3880.7 ^c ± 3.1	7.20	4202.5 ± 4.3	9.65	2446.6 ± 3.6	4.19	6511.7 ^a ± 3.3	11.15	1571.4 ± 3.6	2.69

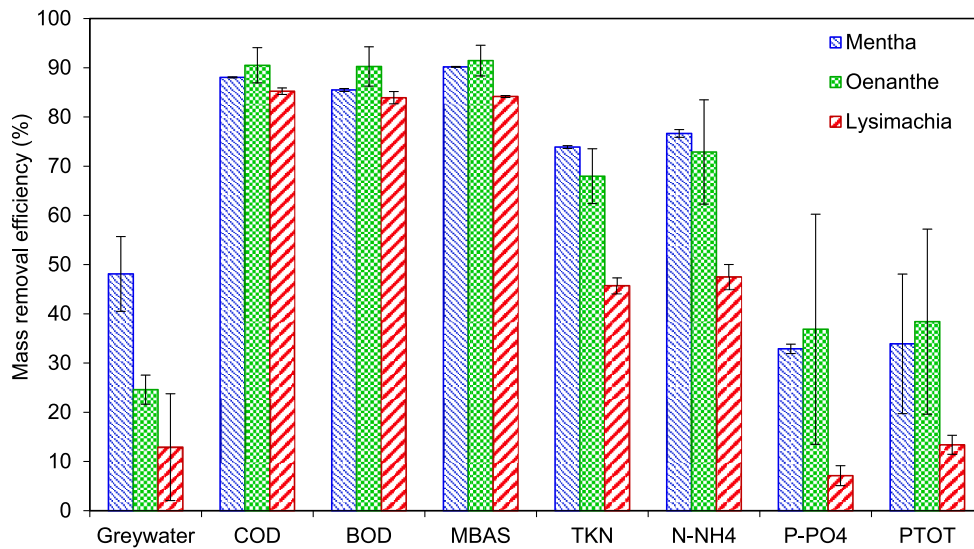


Fig. 2. Mass removal efficiency of inflow greywater and rainfall volumes and monitored pollutants during the 2-year experiment.

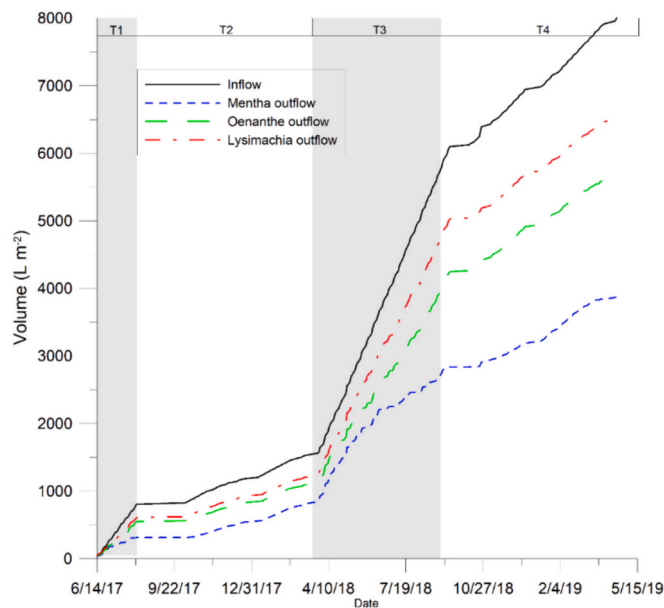


Fig. 3. Cumulative inflow and outflow volumes ($L m^{-2}$) over the 2-year experiment in the different VGS lines.

$2.9 L m^{-2} d^{-1}$ during winter 2018. In summer, the estimated ET increased up to an average of $6.5 L m^{-2} d^{-1}$, soon after vegetation stabilization (2017), and further increased in 2018 up to averages of $7.6 L m^{-2} d^{-1}$. Mentha was also the species that exhibited the highest evapotranspiration (ET) during the summer monitoring period of 2018, reaching values as high as $10.2 L m^{-2} d^{-1}$ which were comparable to those reported in previous studies by Tamiazzo et al. (2015). In contrast, such values were much larger than the ET estimates provided by Prodanovic et al. (2019a) in green wall systems treating greywaters (average = $4.3 L m^{-2} d^{-1}$) under similar climatic conditions in Australia, suggesting that plant species selection –e.g. they used *Carex appressa* L.– and green wall management –e.g., they used a single plant per pot of $0.2 \times 0.2 m$ – can be significant factors that affect the VGS water balance.

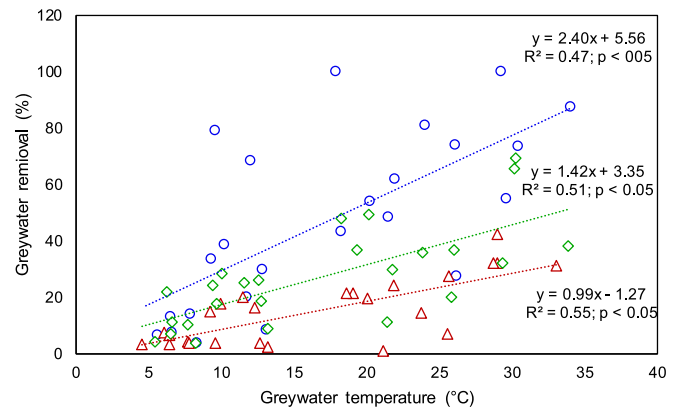


Fig. 4. Relation between greywater temperature in the different vegetated lines (circle marks = Mentha; diamond marks = Oenanthe; triangle marks = Lysimachia) during the 2-year experiment, and greywater mass removal.

Also, our results indicate a higher evapotranspiration potential compared to the study by Segovia-Cardozo et al. (2019). In their 4-month experiment on a pot-based green façade, they calculated a landscape coefficient of evapotranspiration –the ratio between actual and reference evapotranspiration– based on microclimate conditions, plant species, and canopy density using tap water for irrigation. Their coefficient never exceeded 1.0, whereas our estimated crop coefficient (ET/ET_0^{-1} , Tables 2, 4) averaged 1.7, with values exceeding 3.0 for Mentha (see supplementary Table S9 for details). The likely reason for these differences is the selection of plant species beyond different climatic conditions. Segovia-Cardozo et al. (2019), in fact, used a mix of species, not exclusively macrophytes, and did not create saturation conditions due to free drainage within the pots. However, care must be taken when applying our estimates to other contexts, as the ratio is strongly influenced by factors such as water management practices, particularly the volume of greywater inflow.

3.3. Pollutant mass removal

Over the entire experiment, the same effluent fed the different vegetated lines, and the total mass of pollutants that entered the system was equal to: COD = 5864.2 g m⁻², BOD₅ = 1958.8 g m⁻², MBAS = 134.3 g m⁻², TKN = 205.7 g m⁻², N-NH₄ = 88.2 g m⁻², N-NO₃ = 0.1 g m⁻², P-PO₄ = 54.3 g m⁻², P_{tot} = 115.1 g m⁻² (Figs. 3 and 4). Overall, the average of total outflow pollutants across the VGS vegetated lines was as follows: COD = 708.4 ± 78.9 g m⁻², BOD₅ = 263.4 ± 31.8 g m⁻², MBAS = 15.3 ± 2.2 g m⁻², TKN = 57.8 ± 8.7 g m⁻², N-NH₄ = 30.3 ± 5.7 g m⁻², N-NO₃ = 1.3 ± 0.4 g m⁻², P-PO₄ = 40.4 ± 4.6 g m⁻², P_{tot} = 57.8 ± 7.0 g m⁻². Among treatments, *Lysimachia* was always the least effective to remove pollutants, despite differences being significant only for the TKN (*p* < 0.05). In contrast, *Oenanthe* and *Mentha* had not statistically different performances with respect to the organic compounds (COD, BOD₅, MBAS), P-PO₄ and P_{tot}, TKN and N-NH₄. Regarding N-NO₃, it was the only parameter that showed a greater outflow mass (1.30 ± 0.37 g N m⁻²) compared to inflow (0.10 g N m⁻²).

During the summer period, the total loading of COD, BOD₅ and TKN increased from 2017 to 2018 by an average of +39 % due to the intensification of greywater input that was arbitrarily established in the VGS (details in Table 1). The MBAS even reached higher values up to +71 % during the same period (Fig. 5), due to some fluctuations in greywater quality inputs. Anyway, the loading rate of MBAS was generally very low (0.3 g m⁻² d⁻¹) compared to the other organic compounds, which had average loading rates of 13.8 and 4.7 g m⁻² d⁻¹ for COD and BOD₅, and was even lower than TKN whose loading averaged 0.7 g m⁻² d⁻¹ during the summers, of which the minor part was in the form of mineral ammonium (N-NH₄ = 0.18 g m⁻² d⁻¹). Similar daily inflow values were applied during the winter, with a maximum organic load of 16.5 g m⁻² d⁻¹ (COD) during the winter of 2017, while N-NO₃ was negligible due to predominantly anoxic conditions (Dal Ferro et al., 2021). Each vegetated treatment line was able to remove most of the total inflow organic compounds reaching performances >90 % for COD, BOD₅ and MBAS with *Oenanthe*. Slight and not significant performance reductions were observed for *Mentha* and *Lysimachia* regarding the same organic pollutants (Fig. 2). Even most of the nitrogen was removed by the VGS, being TKN and N-NH₄ inflow mass parameters reduced in the outflow of 71.9 % and 65.7 %, on average, with some smaller reduction in *Lysimachia* (59.3 % and 47.5 %, TKN and N-NH₄ respectively) compared to better performances that were estimated in *Oenanthe* (76.0 % and 72.9 %, TKN and N-NH₄ respectively) and *Mentha* (80.4 % and 76.7 %, TKN and N-NH₄ respectively). Except for N-NO₃, which exhibited negative performance despite its negligible total mass (Fig. 6), some removal was also observed for both P-PO₄ and total phosphorus (P_{tot}), with performance levels never exceeding 37 % (in *Oenanthe*) (Fig. 2).

The capability of space-saving green walls to treat greywaters and remove most of the pollutants from the inflow was already found in previous research (Sami et al., 2023), where different substrates were compared in a vegetated green wall. The authors found that COD and BOD₅ were removed by >96 % with pumice and biochar as substrates and water inflow like ours, and notably the performance was maintained very high even with greater water inflows, emphasizing to ability of green wall systems to buffer any load peaks of organic compounds that could occur, especially when the growing material with high specific surface and adsorption capacity like biochar was used (Dalahmeh et al., 2014). Under the peculiar conditions of our experiment, removal performance based on mass was superior to that based on concentrations (Dal Ferro et al., 2021), suggesting that retention times was large enough to maximize evapotranspiration, especially in the summer temperatures, and to likely increase pollutant concentrations in the outflow greywaters, reducing the overall performance to 83 % and 43 % for COD and TKN, respectively. In contrast, when calculated in terms of mass, the performance was 88 % and 62 %. However, it is likely that VGS management with higher greywater input during the summer masked

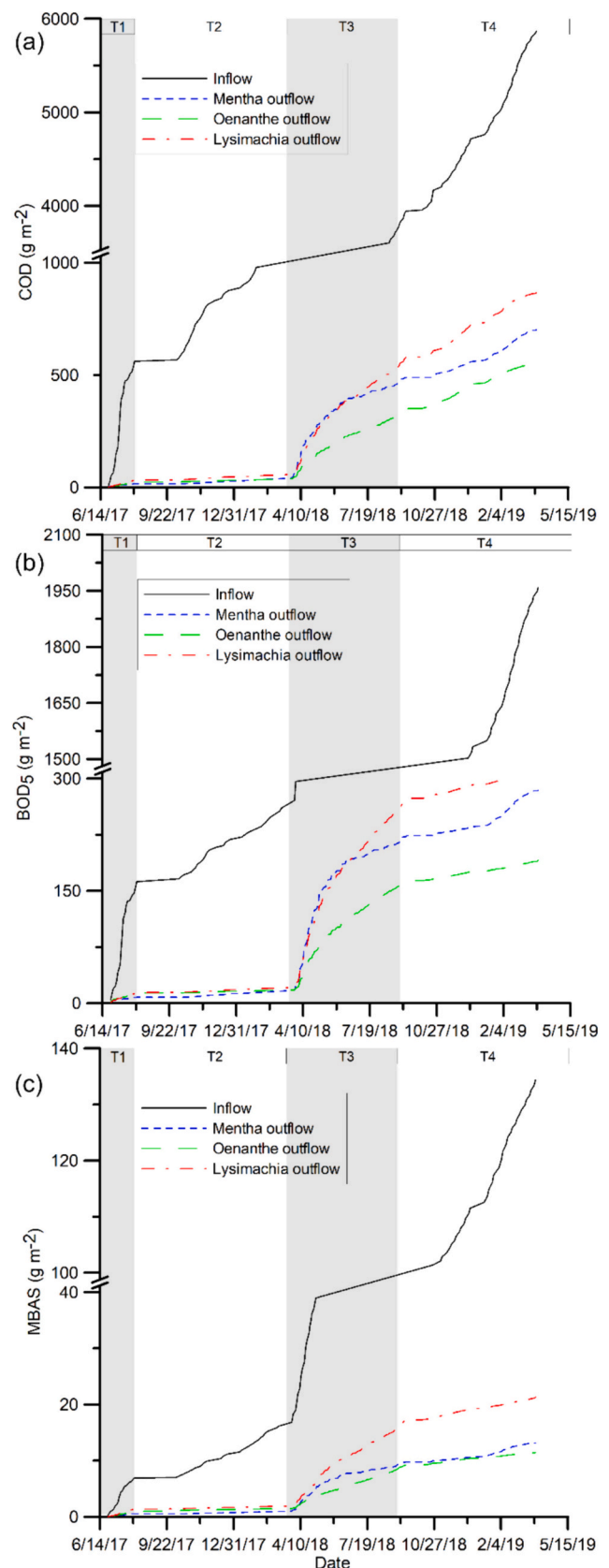


Fig. 5. Cumulative inflow and outflow masses (g m⁻²) of monitored greywater pollutants (a, COD; b, BOD₅; c, MBAS) over the 2-year experiment in the different VGS lines.

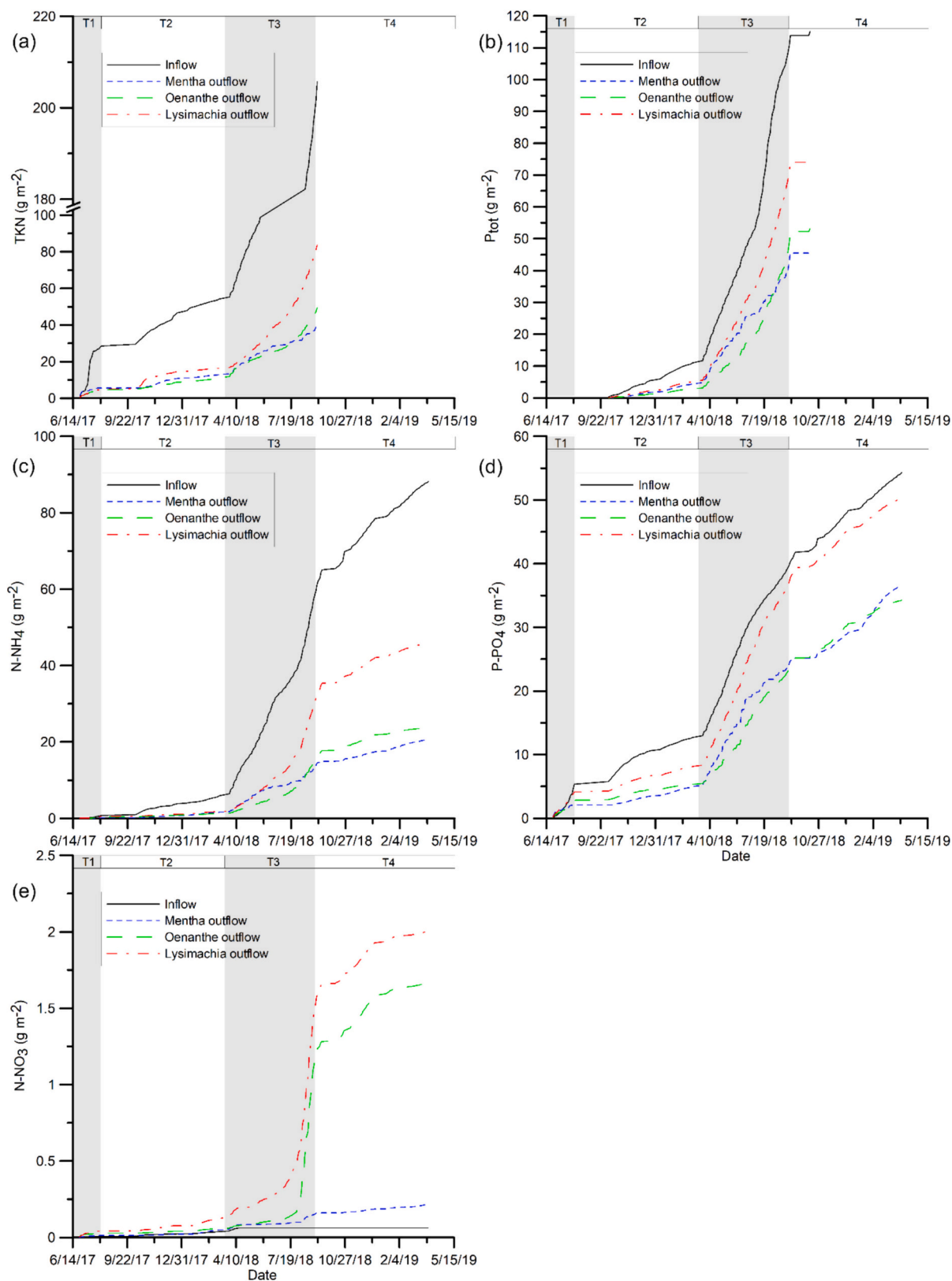


Fig. 6. Cumulative inflow and outflow masses (g m⁻²) of monitored greywater pollutants (a, TKN; b, P_{tot}; c, N-NH₄; d, P-PO₄; e, N-NO₃) over the 2-year experiment in the different VGS lines. To note that TKN and P_{tot} were not measured during Summer 2017 and Winter 2018, respectively.

Table 5

Pearson's correlation matrix between greywater temperature and greywater parameters according to different vegetated line. Significant correlation coefficients (r) are reported in bold ($p < 0.05$).

Percentage removal (%)	Greywater temperature		
	Mentha	Oenanthe	Lysimachia
COD	0.06	-0.19	-0.22
BOD ₅	0.05	-0.38	-0.42
MBAS	0.07	-0.43	-0.68
TKN	0.44	0.18	-0.02
N-NH ₄	0.39	0.05	-0.08
N-NO ₃	0.55	0.60	0.37
P-PO ₄	0.03	-0.20	-0.32
P _{tot}	0.20	0.22	0.00

the greatest pollutant removal processes that usually occurred during summer seasons (Addo-Bankas et al., 2021) when nutrients vegetation uptake and microbial degradation processes are maximized, as shown by the relationships between temperature and pollutant mass removal that were often not significant, or even negative with respect to the positive expected ones (Table 5). It is worth noting that our VGS was covered by a plastic film during winter, which mitigated microclimate conditions and may have partially enhanced plant growth and treatment performance. However, in the context of real-world management of a VGS supplied with greywater, it is likely that greywater temperature remains relatively stable and usually $>18\text{ }^{\circ}\text{C}$ (Oteng-Peprah et al., 2018). These high temperatures observed during winter can be due to warm water from personal hygiene and cooking activities, suggesting that the actual conditions are not that different from those tested in this experiment. Moreover, a reduction in wind speed would occur, with implications such as plants benefiting from the heat lost from building envelopes and energy savings in colder seasons (Perini et al., 2011).

3.4. Nutrients plant uptake

Vegetation sampling that was conducted during the growing season 2018 provided interesting results regarding the potential of nutrients uptake. Despite the concentration of nitrogen in aboveground Mentha vegetation at harvest (September 10th) was significantly lower (1.53 %) than in Lysimachia (2.50 %) and in turn in Oenanthe (3.34 %), the total N removal did not change between species (Table 6) being the Mentha biomass much greater than the others. On average, the N uptake was 14.6 g m^{-2} across the vegetated lines of the VGS, ranging between a minimum of $2.2 \pm 0.9\text{ g m}^{-2}$ in Oenanthe and a maximum of 62.8 g m^{-2} in Mentha. To note that in both cases (maximum and minimum data) the values were found in the upper-level position of the VGS, where Mentha and Oenanthe behaved differently because of the raw greywater.

Table 6

Average values (\pm standard error) of nitrogen (N) and phosphorus (P) concentration and uptake by aboveground vegetation at harvest.

Plant species	In-series vegetation position	N biomass concentration (%)	N biomass uptake (g m^{-2})	Estimated N removal with vegetation (%) ^{a,b}	P biomass concentration (%)	P biomass uptake (g m^{-2})	Estimated P removal with vegetation (%) ^a
Mentha	Upper level	1.70 ± 0.0	47.8 ± 15	14.3 ± 3.9	0.45 ± 0.02	13.3 ± 3.4	7.0 ± 1.5
	Medium level	1.60 ± 0.13	18.7 ± 4		0.51 ± 0.01	5.7 ± 1.5	
	Lower level	1.29 ± 0.2	6.9 ± 1.6		0.47 ± 0.00	2.5 ± 0.2	
	Average	1.53 ± 0.1	24.5 ± 8.7		0.49 ± 0.00	7.2 ± 2.2	
Oenanthe	Upper level	3.66 ± 0.35	3.2 ± 0.9	5.4 ± 0.7	0.47 ± 0.00	0.7 ± 0.5	2.0 ± 0.2
	Medium level	3.55 ± 0.14	9.2 ± 1.1		0.48 ± 0.02	2.0 ± 0.1	
	Lower level	2.83 ± 0.1	12.1 ± 1		0.76 ± 0.01	3.4 ± 0.3	
	Average	3.34 ± 0.19	8.2 ± 1.7		0.76 ± 0.01	2.0 ± 0.6	
Lysimachia	Upper level	$2.7 \pm \text{n.a.}$	$11.1 \pm \text{n.a.}$	7.36 ± 1.2	0.28 ± 0.02	$1.3 \pm \text{n.a.}$	1.4 ± 0.1
	Medium level	$2.6 \pm \text{n.a.}$	$10.9 \pm \text{n.a.}$		0.33 ± 0.00	$1.6 \pm \text{n.a.}$	
	Lower level	2.2 ± 0.3	11.2 ± 5.4		0.39 ± 0.00	1.3 ± 0.3	
	Average	2.5 ± 0.2	11.1 ± 3.1		0.33 ± 0.02	1.4 ± 0.2	

^a Percentage removal with respect to inputs in the growing season.

^b Estimated N input from TKN data.

Previous studies (Sun et al., 2022) have demonstrated that Oenanthe can establish and grow without any stress even at high concentrations of N-NH₄ up to 400 mg L^{-1} , resulting in nitrogen concentrations in vegetation between 5 % and 6 % compared to our findings. Other ornamental plants, such as *Lonicera japonica* Thunb. and *Callistemon viminalis* (Sol. ex Gaertn.) G. Don, that were recently tested in Greece seemed promising to adapt to confined wetlands systems in urban environment to treat greywaters, while others such as *Trachelospermum jasminoides* (Lindl.) Lem. suffered from plant stress, especially organic (COD) loading rates of $358 \pm 194\text{ mg L}^{-1}$ (Stefanatos et al., 2023). This suggests that it is required to monitor water quality parameters other than the primary nutrients to identify the source of vegetation stress. The vegetated lines performed slightly different in terms of N uptake ($p = 0.09$), while significant differences ($p < 0.05$) were observed for P removal. In the first case, on average, Mentha effectively removed $24.5 \pm 8.7\text{ g m}^{-2}$ compared to Oenanthe and Lysimachia that had an uptake of 8.2 ± 1.7 and $11.1 \pm 3.1\text{ g m}^{-2}$, respectively. Regarding phosphorus, the highest concentration was found in Oenanthe ($0.76 \pm 0.01\%$), followed by Mentha ($0.49 \pm 0.00\%$) and finally Lysimachia ($0.33 \pm 0.02\%$) which determined, in combination with biomass production, a significant higher uptake in Mentha ($7.2 \pm 2.2\text{ g m}^{-1}$ on average) compared to Oenanthe ($2.0 \pm 0.6\text{ g m}^{-1}$ on average) and in turn Lysimachia ($1.4 \pm 0.2\text{ g m}^{-1}$ on average). Overall, the vegetation contributed to remove in aboveground harvested biomass 9.7 % of the N input in the growing season aligning with literature values (Vymazal, 2007). Also, to note the pivotal role of vegetation in the removal of phosphorus as already emphasized by Prodanovic et al. (2019b), that reported an increase in P removal efficiency over a 1-year experimental time from 18 % to 32 % that was related to vegetation growth. Similarly, we observed that the best-performing growing vegetation –Mentha– retained P over time, with an uptake in vegetation of 7 % compared to the total input at the end of the of the growing season (Table 6).

4. Conclusions

The water and pollutant mass removal of a living wall system comparing different vegetation species was examined in a two-year experiment. The results show that living walls can be designed as a promising technology for on-site kitchen greywater treatment and inflow water reduction, with the further potential to buffer any variability in the incoming effluent. In fact, the tested VGS after two years was able to remove greywater inflow volumes up to almost 50 % ($> 12\text{ L m}^{-2}\text{ d}^{-1}$) using Mentha compared to Oenanthe and Lysimachia, suggesting it as a suitable species in green wall systems even with raw greywater input. Moreover, most of the mass of organic compounds ($>85\%$) and nitrogen ($>60\%$) input were removed, with increasing potentials for phosphorus filtering mediated by vegetation

establishment.

On the other hand, *Mentha* is less suitable if the recovery of treated water is an objective, especially in water-scarce areas where even poor-quality water becomes a valuable resource that should be valorised. However, the combination of different vegetation species is suggested, being for instance *Oenanthe* growing more rapidly than *Mentha* at the beginning of the growing season following some greywater treatment. Future studies should attempt to find the best combination of established vegetation along a vertical green wall to maximize year-round water and pollutant removal.

CRedit authorship contribution statement

Nicola Dal Ferro: Data curation, Methodology, Writing – original draft, Writing – review & editing. **Nicola Celadon:** Writing – original draft. **Maurizio Borin:** Writing – review & editing, 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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2024.176384>.

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