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Original
Vertical greening systems and green roofs for greywater treatment and reuse: experiment-based recommendations for research and practice / Rizzo, A.; Sarti, C.; Masi, F.; Costamagna, E.; Boano, F.; Pucher, B.. - In: JOURNAL OF ENVIRONMENTAL MANAGEMENT. - ISSN 1095-8630. - ELETTRONICO. - 408:(2026), pp. 1-14. [10.1016/j.jenvman.2026.129928]

Publisher:
Elsevier

Published
DOI:10.1016/j.jenvman.2026.129928

Journal of Environmental Management 408 (2026) 129928

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

Vertical greening systems and green roofs for greywater treatment and reuse: experiment-based recommendations for research and practice

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ARTICLE INFO

Keywords:
Nature-based solutions
Vertical greening system
Green wall
Green façade
Green roof
Greywater
Circular economy

ABSTRACT

The increasing greening of urban areas to deliver multiple benefits is expected to face water-related challenges, as irrigation demand during drought periods can negatively affect drinking water supply. Consequently, the implementation of Nature-based Solutions (NbS), such as vertical greening systems and green roofs, should be combined with the use of greywater as alternative water source, enforcing a circular economy perspective. Both vertical greening systems and green roofs can either be irrigated with greywater or designed to act as decentralized and non-conventional water treatment plants, providing treated water for non-potable purposes.

Although this topic has received increasing attention in recent years across different fields, clear design recommendations for urban NbS using greywater are still lacking. This research addresses this gap by analysing experimental studies published in scientific journals and grey literature, and by developing recommendations to improve both experimental design and practical implementation of vertical greening systems and green roofs for greywater use. The recommendations merge geometrical aspects (such as substrate depth and rooftop slope) with operational conditions (such as hydraulic/organic loading rate and hydraulic retention time) and are differentiated according to the main objective of the technology: direct greywater reuse (i.e., total evapotranspiration approach) or treatment and reuse for other non-potable-purposes. The findings of this analysis have been compared with the well-established field of treatment wetlands, setting the basis for a common approach and supporting the wider adoption of these sustainable technologies in urban environment.

1. Introduction

The world is facing an increasing demand for clean water due to population growth and socio-economic development (UN, 2024; Zucchinelli et al., 2021). Climate change is expected to further stress water resources because of the higher intermittency of the precipitation regime driven by the intensification of the water cycle (Parmesan et al., 2022). The introduction of Nature-based Solutions (NbS) in urban areas has been advised as an important strategy of mitigation and adaption of climate change (European Commission. Directorate General for Research and Innovation, 2015). However, as highlighted by Pearlmutter et al. (2021), the implementation of NbS in the built environment entails increases in water use to ensure full functionality, including their cooling effect (Gräf et al., 2021).

The reuse of reclaimed wastewater represents a key strategy to address these challenges (Mannina et al., 2022). In addition to rainwater, which may not always be a reliable resource (Prenner et al., 2021), wastewater has high potential to substitute valuable drinking water for non-potable uses. In particular, when source separation is applied, greywater (household wastewater excluding the toilet) is well suited for treatment and reuse, due to its moderate contamination levels and continuous production (Boano et al., 2020; Hadengue et al., 2022). Even though greywater contains low amounts of contaminants, a relatively mild treatment is necessary before its reuse for irrigation, and previous studies (e.g., Arden and Ma, 2018; Garrido-Baserba et al., 2024; Masi et al., 2018; Pearlmutter et al., 2021) have proposed a decentralized approach to greywater treatment using NbS with minimal energy consumption (Arden and Ma, 2018). Given the limited availability of

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https://doi.org/10.1016/j.jenvman.2026.129928
Received 4 July 2025; Received in revised form 24 April 2026; Accepted 7 May 2026
Available online 12 May 2026

ground space in urban areas, the treatment systems can be implemented on walls or roofs through the use of vertical greening systems (VGS) and green roofs (Cross et al., 2021). The interest on these NbS paved the way to studies on their application for greywater treatment, including both research papers and review articles. For example, Pradhan et al. (2019) reviewed the use of green roofs and VGS for greywater recycling, focusing on contaminant removal mechanisms in soil and plants, as well as on social, economic and cultural barriers for the implementation of these NbS. The authors conclude the need for design considerations addressing system design and clogging prevention. Later, Boano et al. (2020) reviewed the available applications of green roofs and VGS for greywater treatment, analysing the links between key operational parameters (i.e., hydraulic loading rate, HLR; organic loading rate, OLR; hydraulic residence time, HRT; oxygen consumption rate, OCR) and contaminant removal efficiency. The authors reported that HLR values up to 500 $L\ m^{-2}\ d^{-1}$ were associated with high removal of organic matter, total nitrogen and total suspended solids. Petreje et al. (2023) developed a hybrid treatment wetland (TW) – green roof system, in which a dedicated treatment units supply irrigation water to the adjacent green roof. The role of VGS was further explored by Addo-Bankas et al. (2021), who emphasise the need to better quantify the role of different growing media and vegetation species on contaminant removal and stressed the importance of including a disinfection step to limit health risk associated with greywater reuse. This aspect is particularly relevant for urban agricultural applications on green roofs or VGS (Canet-Marti et al., 2021), where the EU water reuse directive applies (EU, 2020). More recently, Galvão et al. (2025) reviewed greywater contaminant removal performances in VGS under different configurations and climatic conditions, and provided predicting equations for areal mass removal depending on influent areal mass load. Finally, Pucher et al. (2025) reported comparable performance across VGS treating greywater, suggesting that treatment efficiency is strongly influenced by the operational parameters (loading rates, feeding intervals) as well as by the selection and hydraulic properties of the filter media. Despite this growing body of knowledge, implementation and mainstreaming are still hindered. It is important to stress that the application of NbS for treatment of GW is currently hampered by multiple barriers. Firstly, costs - mostly related to construction and maintenance - represent a critical factor that limits the diffusion of NbS, including those for GW treatment. Different studies stressed that the assessment and inclusion of benefits of NbS is important to comprehensively quantify the net economical value of NbS (e.g., (Neumann and Hack, 2022; Ruangpan et al., 2024), including green roofs and VGS (Teotónio et al., 2021). Another critical factor is the lack of clear standards and guidelines, as identified by Castellar et al. (2024), Martin et al. (2025) and Prodanovic (2025). Even when opportunities exist for reuse of GW, there is a paucity of established indications to guide the design of VGS and green roofs to treat GW. This fact is reflected in a wide range of structural and operational configurations proposed for these systems (e.g., (Pucher et al., 2025), and results in uncertainty on how to develop efficient and reliable NbS for GW reuse.

Conventional review papers are generally not suitable as a basis for developing design recommendations, as they mainly provide an overview of existing scientific findings. In contrast, the present study adopts a different approach by combining insights from the literature with available project data, with the aim of formulating design recommendations grounded in the extensive experience gained from treatment wetland design. This methodological approach, identified as a key factor by Pucher et al. (2025), is applied to the present work to support the development of practical and transferable recommendations for NbS used in greywater treatment.

2. Material and methods

2.1. *Nomenclature of vertical greening systems and green roofs*

2.1.1. *Vertical greening systems*

VGS are defined as NbS integrated in the vertical building envelope. The nomenclature of VGS is used inconsistently in literature. In this study, we adopt the recently proposed nomenclature of NbS units by Langergraber et al. (2021) and specifically discussed by Pearlmutter et al. (2021). Three types of VGS are recognised: ground-based, pot-based and pocket-based green systems.

Ground-based green façades (Fig. 1A) are characterized by the ground-based root zone, from which climbing plants, either evergreen or deciduous, grow vertically upwards, either directly on the façade or by using climbing aids. The plant growing media may consist of in-situ soil or specific technical substrates.

Pot-based green walls (Fig. 1B, also known as living walls) are characterized by the use of pots or containers mounted on the wall and filled with soilless technical substrates, soil, or a combination of both. In some cases, these systems are designed similarly to green roofs, with multiple functional layers (e.g., substrate, filter, and drainage layers). This configuration allows the use of a wide range of plant species, including climbing plants, shrubs, perennials and small trees. Pocket-based green systems (Fig. 1C) consist of panels and engineered structures filled with soilless technical substrates and fully planted vertically. Some systems include removable panels for seasonal adjustments, e.g. during winter. Although pocket-based systems support a wider range of plant species compared to ground-based façades, they generally require more maintenance due to their nutrient supply and irrigation systems. The durability of these installations largely depends on the selected panel type.

2.1.2. *Green roofs*

Green roofs are vegetated systems installed on building roofs, typically composed by a vegetation layer, a substrate layer supporting plant growth, and a drainage system (Fig. 2). According to the common classifications, three types of green roofs can be distinguished based on their depth: extensive (medium depth up to 150 mm), semi-intensive (150-250 mm) and intensive green roofs (medium depth over 250 mm) (Calheiros and Stefanakis, 2021; Pearlmutter et al., 2021). Green roofs used for greywater treatment can be assimilated to modified treatment wetland (TW) operating in horizontal or vertical flow regime. Importantly, the plant growing media may differ from those typically used in TW (e.g. sand 0-4 mm or gravel 4-8 mm) due to structural constraints related to roof load. This issue needs to be considered when defining specific design requirements (Cross et al., 2021).

2.2. *Research design*

2.2.1. *Dataset collection*

In this study, scientific and grey literature were collected and analysed to build a robust dataset for the development of practical design recommendations for VGS and green roofs used for greywater treatment and reuse. Current experimental studies from the scientific literature were selected through a systematic review carried out using the Scopus and Web of Science databases. Two parallel searches were performed for VGS and green roofs using the search string reported in Table 1. The temporal scope of the literature search was defined by considering only publications available up to May 2025, while no limit was imposed to exclude old publications since the research field is relatively recent. Citation analysis was also applied to identify recent developments building on key references, such as Boano et al. (2020).

Search results were further screened to include only publications that satisfy the following criteria.

1. Publications written in English;

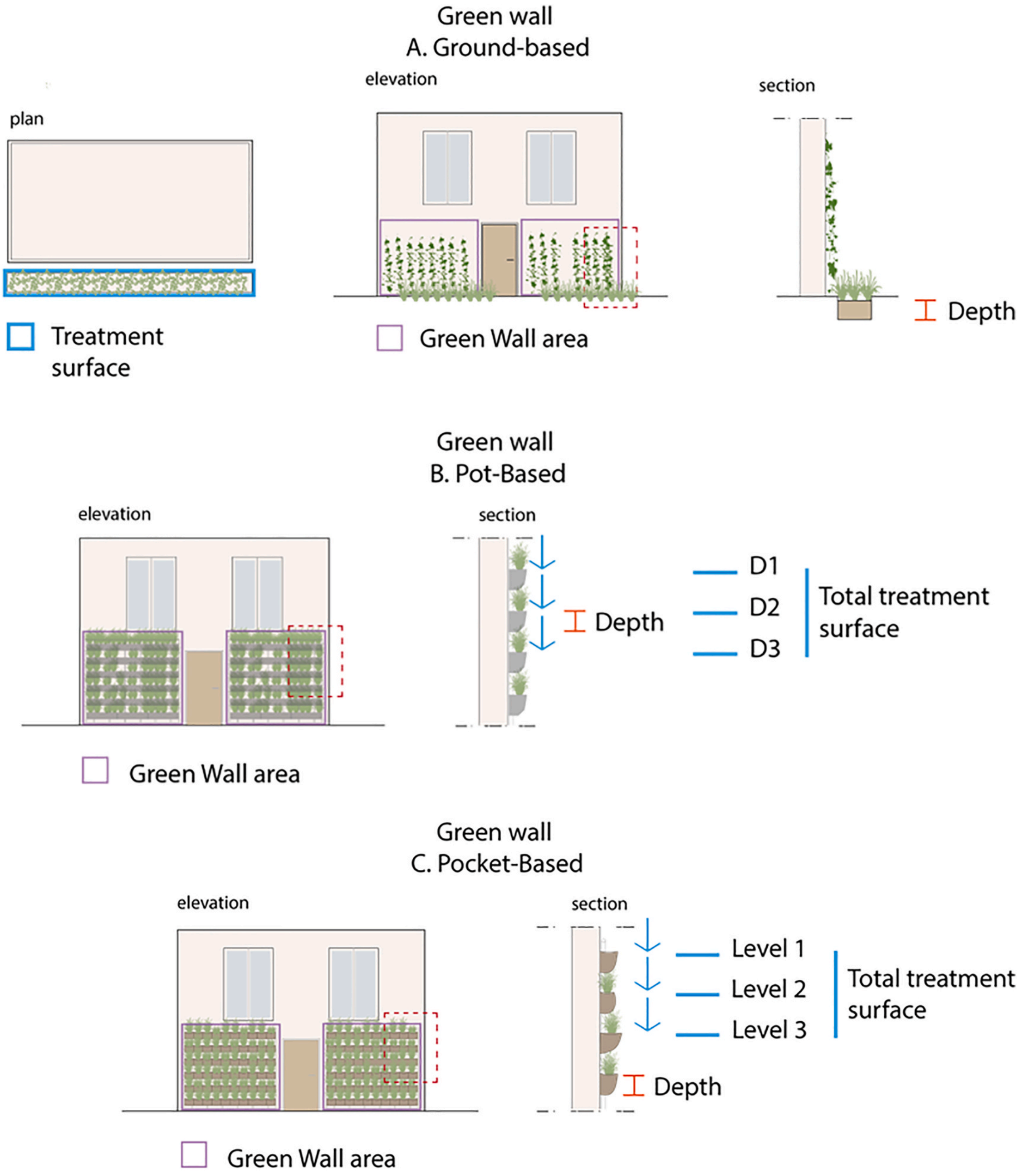

Fig. 1. Plan, elevation and section of three types of VGS: (a) ground based, (b) pot based, (c) pocket-based).

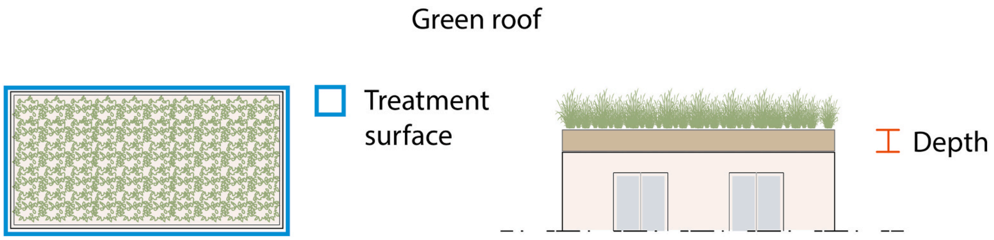

Fig. 2. Schematisation of key dimension parameters of a green roof.

2. Publications that report quantitative design and water quality data: the selection focused on studies providing quantitative information on system design and performance, including hydraulic and organic loading rates, pollutant removal efficiency, substrate characteristics, and vegetation types, together with clear descriptions of system configuration and operation;
3. Publications from actual VGS or green roof installations: to ensure practical relevance, priority was given to pilot- and full-scale

Table 1
Search strings used for identifying experimental studies on VGS and green roofs treating greywater.

System	Search string
VGS	(((wall* OR living* OR facade* OR vertical) AND green*) AND (gr?ywater OR "gr?y water"))
Green roofs	((greenroof OR "green roof") AND (gr?ywater OR "gr?y water"))

systems, i.e. , excluding studies that presented results from column and mesocosm experiments; .

4. Grey literature was restricted to high-quality reports and deliverables from established EU-funded projects and experienced professional actors.

2.2.2. *Identification of design parameters*

VGS and green roofs for greywater treatment and reuse are characterized by a variability in their design approach. To enable a coherent comparison across different systems, two steps are needed: (1) classification based on the main design concepts and (2) identification of the key design and comparison parameters. Pucher et al. (2025) proposed a list of relevant design and operational parameters for the consistent description of VGS for greywater treatment. This list was adapted from Langergraber et al. (2020), who defined the parameter to be listed for TWs. As a result, the same parameter list can also be used for green roofs. The main parameters considered in this study are summarised in Table 2. The geometrical design parameters are also graphically represented in for VGS and green roofs in Figs. 1 and 2, respectively.

3. Results and Discussion

3.1. *Analysis of design approaches*

After applying the eligibility criteria described in Section 2.1.1 and completing the expert-judgement refinement, 29 VGS papers were selected from an initial set of 157 screened publications within the timeframe 2008 - May 2025 (total from both Web of Science and Scopus databases). The VGS dataset includes 18 peer-reviewed studies selected in collaboration with the Green Wall Cluster of the Circular City COST Action (Pucher et al., 2025). These studies focus on vertical systems treating greywater or similar water streams and are mostly based on pilot- or full-scale applications in urban environment. They address a range of design and operational aspects, including system layout (e.g., modular or continuous), growing media and plant selection, loading rates, treatment performance, and maintenance. Overall, the dataset was assembled to capture recent innovations and to identify robust and transferable design principles.

Table 2
Main design and operational parameters of VGS and green roofs for the data analysis based on Langergraber et al. (2020) and Pucher et al. (2025).

Parameter	VGS	Green Roofs
Area	Total surface area of all elements	Surface area
	Surface area per level	-
	Vertical area covered by the VGS	-
n° levels	Number of levels of pots or modules	-
Plant growing media	Description of the components used	
Plant growing media volume	Volume per level	Volume of the green roof media
Depth	Media depth in the pots or modules	Depth of the media
Weight	Weight of the media in the pot or module	Overall weight of the media
HLR	Overall and specifically in the first level	Overall
OLR	Overall and specifically in the first level	Overall
OCR	Overall	Overall
COD concentration	Influent and effluent concentrations and calculated removal rate	

For green roofs, 16 peer-reviewed scientific papers were identified as relevant from 88 screened publications. These studies address substrate composition, vegetation types, hydraulic design, treatment efficiency, and long-term system behaviour. While some focus specifically on greywater treatment, others provide general design data applicable to such applications. Where available, review papers were also included to synthesize common trends and recurring challenges across multiple studies, thereby supporting a broader understanding of best practices in green roof design for greywater reuse. The selected literature is reported in Table 3.

The development of robust design criteria for VGS and green roofs used in combination with greywater use and reuse is challenged by the high diversity of design approaches reported in literature. General design principles for VGS and green roofs are addressed in national guidelines (e.g. FLL, 2018) and scientific publications. However, with respect to water management, green roofs are mainly discussed in relation to stormwater management benefits (e.g. Boano et al., 2020; Cook and Larsen, 2021; Yan et al., 2024), while detailed information for VGS remain limited (Prenner et al., 2021). Several publications describe the influence of design parameters on performance of VGS (Galvão et al., 2025; Gholami et al., 2023; Prodanovic et al., 2020) but do not provide transferable information on pollutant removal that can be directly used for design purposes.

Overall, there is a connection between these novel NbS for water pollution control and treatment wetlands (TW). As noted by Pucher et al. (2025), VGS treating greywater can be considered a subcategory of TW, and the same apply to green roofs (Cross et al., 2021). Consequently, designs and operational criteria for these systems should build on the extensive knowledge base developed within the established TW community (e.g. Dotro et al., 2017; Kadlec and Wallace, 2009; Langergraber et al., 2020).

3.2. *System classification*

The analysis of the collected datasets is section has led to a general classification of both VGS and green roofs based on their potential of GW reuse. This potential, here quantified by the amount of GW provided per

Table 3
Selected literature works on green walls and green roofs treating greywater.

NbS	Peer-review literature	Grey literature
VGS	(Addo-Bankas et al., 2024; Aicher et al., 2022; Bakheet et al., 2020; Boano et al., 2021a, 2021b; Büngener et al., 2024; Costamagna et al., 2022, 2025; Dal Ferro et al., 2021, 2024, 2021; Estelrich et al., 2021; Galvão et al., 2022; Gattringer et al., 2016; Kotsia et al., 2020; Lakho et al., 2021, 2022; Masi et al., 2016; Obeidat et al., 2025a, 2025b; Pophali et al., 2024; Prodanovic et al., 2018, 2019, 2020; Pucher et al., 2022; Sami et al., 2023; Sarfraz et al., 2023; Stefanatou et al., 2024; Yadav et al., 2023; Zraunig et al., 2019)	Masi (2025); Pucher et al. (2025)
Green roofs	(Agra et al., 2018; Chowdhury and Abaya, 2018; Frazer-Williams et al., 2008; Liu et al., 2021; Nguyen et al., 2021; Petreje et al., 2023; Rahman et al., 2023; Ramprasad et al., 2017; Thanh et al., 2014; Thomaidi et al., 2022; Van et al., 2015; Winward et al., 2008; Xu et al., 2020; Zapater-Pereyra et al., 2013, 2016; Zehnsdorf et al., 2019)	Masi (2025); Masi et al. (2015)

unit area (i.e., HLR), represents the main ecosystem service that is analysed in this paper. However, NbS also provide other ecosystem services and benefits (e.g., thermal insulation, improved aesthetical appearance), which generally increase with the overall area of the NbS (i.e., the vegetation cover). The following subsections discuss the main configurations of VGS and green roofs that can be identified and how they compare in terms of the mentioned ecosystem services.

3.2.1. *Vertical greening systems*

According to the literature review (Table 3, full dataset in Supplementary online material), two different main design approaches can be distinguished based on the HLR: direct irrigation reuse and treatment for further reuse. The first approach focusses on the design of VGS with a low HLR (up to 40 L m^{-2} d^{-1}) that is aimed to sustain the irrigation demand of the plants. This configuration primarily supports direct reuse of greywater for irrigation, and the VGS functions as a recipient of non-conventional water resources. A representative example is the Total Value Wall™ studied by Lakho et al. (2022, 2021), which integrates a pocket-based system operating as a passive irrigation solution with minimal effluent discharge. When treated greywater exceeds irrigation demand, small volumes can be collected and reused.

The second design approach aims to produce treated greywater for further reuse and is based on high HLR values, typically one order of magnitude higher than in the previous design approach (300-1000 L m^{-2} d^{-1} on the first level). These systems prioritize maximizing the volume of treated greywater per square meter of the wall, shifting their primary function from irrigation support to greywater treatment and reuse. This approach is adopted by the Wall2Water system developed

Fig. 3. Overview of alternative design approaches for balancing different ecosystem services of green walls proposed in literature. Dots show the importance of a specific service for each configuration.

within the NAWAMED project (Masi, 2025), which builds on experience gained from the SUPERGREEN project (Boano et al., 2021a, 2021b; Costamagna et al., 2023). By increasing treatment capacity, such systems provide a viable option for decentralized greywater reuse, supporting applications beyond direct irrigation.

An additional, intermediate approach seeks to balance the multiple benefits of green walls through a multipurpose design with HLR values ranging from 40 to 300 L m^{-2} d^{-1} (on the first level). This configuration aims to optimize both the water treatment efficiency and the aesthetic, thermal, and ecological benefits associated with green walls. By integrating flexible operational parameters, these systems are proposed to enhance the multifunctionality of VGS while ensuring effective greywater management (Pucher et al., 2022). This approach represents a promising compromise, enabling both greywater treatment and sustainable reuse while preserving additional environmental and urban benefits.

Depending on the ecosystem services considered, perspectives on the best design approach for VGS dealing with greywater may vary (Fig. 3). When VGS surface coverage is used as an indicator of the aesthetic value, the Total Value Wall™ can be considered as the most favourable option, as it maximizes wall coverage by NbS per volume of treated greywater available for further reuse, whereas Wall2Water performs less favourably under this criterion. When additional ecosystem services commonly associated with green walls are considered (e.g., heat island mitigation, building insulation, noise reduction and biodiversity support) identifying an optimal balance become more complex. In such cases, a dedicated strategy of multifunctional monitoring of green walls treating greywater should be developed, as proposed by Pucher et al. (2022).

Where wall structural capacity is a limiting factor, the literature also identifies a fourth, lower-cost option: narrow ground-based system treating greywater and planted with climbing vegetation to cover the façade (Kotsia et al., 2020; Obeidat et al., 2025a; Stefanatou et al., 2024).

3.2.2. Green roofs

Based on the literature review (Table 3, full dataset in Supplementary online material), and similarly to the analysis of VGS, two main design approaches and implementation schemes for green roofs emerge, based on different HLR values (Fig. 4). The first design approach leads to a zero-discharge system characterised by a low HLR of about 4 L m^{-2} d^{-1}, e.g., the Wetroof proposed by Zapater-Pereyra et al. (2016, 2013). In this configuration, low HLR values are mainly associated with direct greywater reuse for irrigating the green roof using an alternative water resource, with the additional possibility of collecting and reusing small volumes of treated greywater exceeding irrigation demand. On the other hand, green roofs designed with HLR values at least one order of magnitude higher aim to maximize the treated water volume per roof area. In this case, the primary function shifts towards the production of a significant amount of treated greywater for further reuse. This approach is illustrated by a green roof implementation in Tanzania, as presented by Masi (2025) and Masi et al. (2015).

In analogy with the considerations done for VGS, the assessment of green roof design approaches for greywater reuse also depends on the ecosystem services being prioritised. Considering the green roof surface coverage as an indicator of the aesthetic value, the Wetroof represent the best option, as it maximizes roof area covered by NbS per volume of reclaimed greywater available for further reuse, whereas high-HLR systems are less advantageous under this criterion. The assessment further changes when retrofitting potential is considered. One of the main barriers to widespread green roofs implementation is the structural load capacity of existing buildings, which often limits retrofitting to extensive green roofs (depth <10 cm, weight <100 kg m^{-2}), while intensive green roofs with greater depths and weights are generally restricted to new constructions. Similar opportunities and constraints in terms of retrofitting emerged for the implementation of green roof schemes integrating greywater reuse. Direct greywater reuse following the Wetroof approach (Zapater-Pereyra et al., 2013, 2016) allows roof depth and weight to remain within the range of extensive green roofs, increasing retrofitting and replication potential. However, this retrofitting option remains less viable than conventional extensive green roofs, as the irrigation with untreated greywater requires a sloped roof. On the opposite, despite the use of lightweight filling media (e.g. expanded

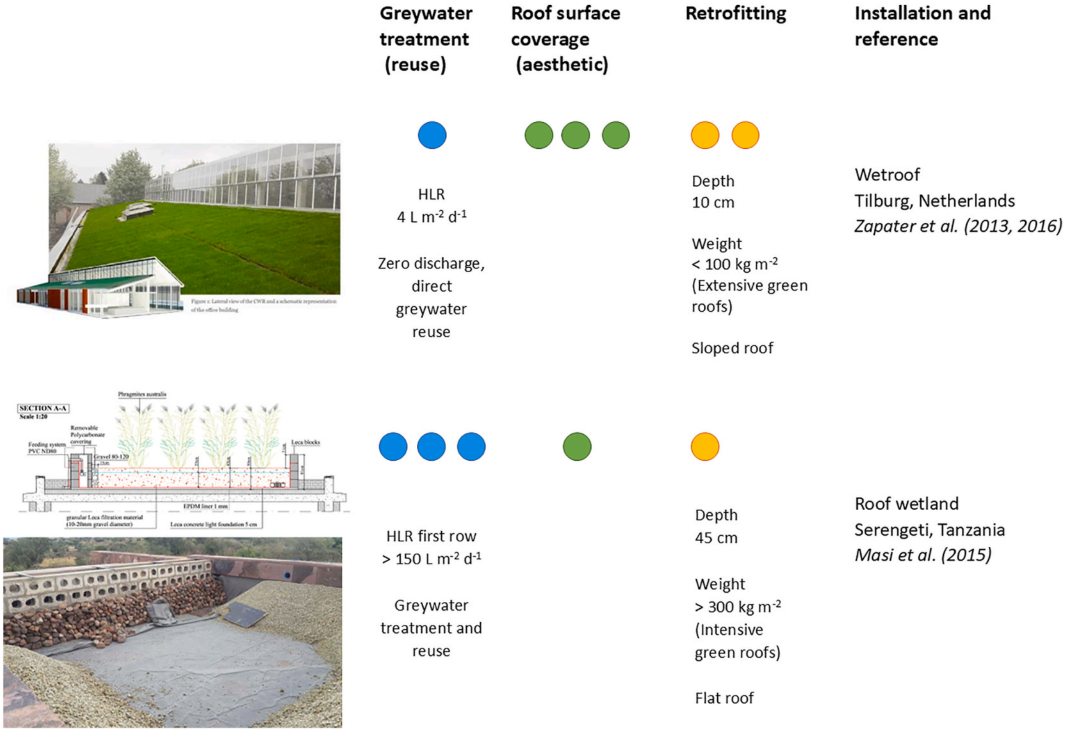

Fig. 4. Overview of alternative design approaches for balancing different ecosystem services of green roof proposed in literature. Dots show the importance of a specific characteristic for each configuration.

clay) and minimized substrate depth (45 cm instead of the typical range of 80 – 100 cm of TWs), the design scheme aimed at maximizing greywater reuse proposed by Masi (2025) and Masi et al. (2015) still reaches a weight (>300 kg m^{-2}) in the range of intensive green roofs, limiting its application mainly to new construction sites.

3.3. General recommendations

In this work, the focus is placed on the NbS specifically applied to greywater treatment; therefore, the following design recommendations refer to specific systems, rather than the overall treatment process. To ensure a holistic and reliable treatment strategy, the inclusion of a degreaser as a pre-treatment unit is strongly recommended, as it plays a key role in protecting downstream NbS from clogging due to sediments and floating material. Similarly, when reuse of treated effluent is planned, the inclusion of a disinfection unit after the NbS system is recommended. Only a limited number of the analysed studies (see dataset in Supplementary online material) report microbiological parameters (such as *faecal coliforms* and *e.coli*), which does not provide a sufficient basis for deriving recommendations on this aspect.

Greywater is often classified as light (from showers, baths, hand basins) and dark (including also kitchens, laundry) to distinguish sources with different strength and treatability. Although these categories are not standardised, they provide a useful indication of influent quality. Light greywater typically shows COD <300 mg/L, whereas dark greywater often exceeds 800 mg/L. These differences are relevant for system design, as dark greywater is associated with higher clogging risks and requires more robust treatment.

3.3.1. Vertical greening systems

Table 4 reports the results of the statistical analysis performed on the VGS dataset (full dataset in Supplementary online material). The main design parameters considered include (i) system depth and number of levels (see Fig. 1 for the definition of levels), (ii) both HLR at the first level and considering all the levels, (iii) OLR at the first level, (iv) HRT and (v) OCR referred to all levels.

Table 5 summarises the main statistical information derived from the literature review on pot- and pocket-based VGS and presents the corresponding design indications according to the system purpose (i.e. direct use or treatment and reuse), in comparison with the established TW guidelines. Each design parameter is discussed, one by one, below, including the comparison with TW literature and the suggested guideline value for designing VGS.

The depth of each level typically ranges between 15 and 25 cm (Table 4). For pot-based green walls, the number of levels described in the literature varies from 3 (e.g., Boano et al., 2021a, 2021b) to 10 (e.g., Pucher et al., 2022). For pocket-based systems, one system presented up to 15 levels using felt modules (Total Value Wall™, (Lakho et al., 2022, 2021). Overall system depth should therefore be selected within a range of 15 to 60 cm, depending on module or pot height and the minimum number of levels. As a conservative assumption, a minimum depth of 15 cm per level with at least 3 levels is recommended, resulting in a total treatment depth of at least 45 cm. OLR on the first level is a key parameter for limiting long-term clogging risk when the main design objective is greywater treatment for further reuse. The range of OLR emerged from the literature analysis (Q1-Q3: 50-157 g_{COD} m^{-2} d^{-1}, Table 4 and Fig. 5 top) significantly exceeds typical OLR limit suggested for TW (<20 g_{COD} m^{-2} d^{-1} for vertical subsurface flow -VF- wetlands filled with 0.2-2 mm coarse sand; Nivala et al., 2018). Since these TW thresholds provide an empirical indication for avoiding bioclogging (i.e., the clogging due to biofilm development for biological treatment of wastewater – Pucher and Langergraber, 2019), a conservative maximum OLR value on the first level of 40 g_{COD} m^{-2} d^{-1} is here suggested. This value remains quite conservative with respect to the VGS literature review, very close to the lowest quartile of analysed values, while still being twice the typical TW design value.

On the other hand, the more established HLR parameter shows less reliability after the statistical analysis. Although VGS have shown a promising resilience with no evidence of short-term clogging even at extremely high HLR values (870 – 1300 L m^{-2} d^{-1} on the first level; Costamagna et al., 2025), more conservative values have been adopted by other authors (100 – 300 L m^{-2} d^{-1}; median value 200 L m^{-2} d^{-1}), which are closer to established design recommendations for TW (<160 L m^{-2} d^{-1} for VF filled with coarse sand 0.2-2.0 mm) and treating greywater (Nivala et al., 2018). Fig. 5 highlights the presence of distinct performance clusters linking OLR and HLR to effluent COD and BOD_5 concentrations in VGS treating greywater. A first cluster (blue circles, Fig. 5) comprises systems achieving effluent concentrations below the upper outflow limits (60 mg COD L^{-1} and 10 mg BOD_5 L^{-1}). Within this group, a clearly defined subset operates below the recommended first-level design thresholds (40 g COD m^{-2} d^{-1} for OLR and 160 L m^{-2} d^{-1} for HLR; Table 5) and consistently delivers compliant effluent quality, confirming the validity of these design indications.

A second cluster includes systems that achieve effluent concentrations below the target limits despite operating above the recommended loading ranges (green circles, Fig. 5), indicating a degree of over-performance and operational resilience under specific design and operational conditions. In contrast, a third cluster represents under-performing systems (red circles, Fig. 5), characterized by effluent concentrations exceeding the upper limits despite nominal compliance with the proposed design criteria. When OLR is used as the primary design indicator, underperformance is limited to a single case exceeding the COD effluent concentration threshold, which corresponds to a wall-based VGS configuration rather than a pot-based system. No systematic underperformance is observed for pot-based VGS within the recommended OLR range, indicating that OLR provides a generally robust predictor of treatment performance across the dataset.

By contrast, when HLR is considered, underperforming cases are more frequent and form a statistically more evident cluster, with multiple systems exceeding effluent COD and BOD_5 limits despite operating within the recommended HLR range. This indicates that HLR alone does not adequately capture the governing treatment mechanisms in VGS, whereas OLR shows a clearer and more consistent relationship with effluent quality. Consequently, OLR is identified as the preferred primary design parameter for VGS treating greywater, while HLR is not recommended as a standalone design criterion.

In analogy with TW design, also OCR can be adopted as a design parameter for VGS operating under conditions similar to VF wetlands (Cross et al., 2021; Dotro et al., 2017). A threshold OCR value of 20 gO_2 m^{-2} d^{-1}, calculated over the whole treatment surface, is suggested. This value is consistent with the statistical analysis of literature data (Q1-Q3:20-40 gO_2 m^{-2} d^{-1}, Table 4) and remains conservative when compared with typical design values for VF wetlands (30 gO_2 m^{-2} d^{-1}, Dotro et al., 2017).

VGSs aiming to treat greywater can also be designed to recreate the operating conditions of horizontal subsurface flow treatment wetlands (HF), i.e., horizontally flowing from levels and continuously fed (Dotro et al., 2017). For these systems, HRT can be assumed as a design parameter. Based on literature review (Q1-Q3: 1.2 – 1.65 days), a minimum HRT of 1 day is recommended. Even if HF wetlands are rarely designed with HRT values below 1 day, even for light greywater treatment, the typical kinetic equations for HF wetlands could support the design of horizontal flow VGS (e.g. Pucher et al., 2022). The statistical analysis indicates that, under the proposed design conditions for OLR and OCR, and for influent BOD_5 concentration in the revised range (17 – 307 mg L^{-1}), effective BOD_5 removal (>80%) and compliance with strict law requirement for BOD_5 effluent concentration (<10 mg L^{-1}) can be expected (Table 4). Instead, the use of HLR on the first level as a design reference is not recommended, due to the need for further investigation into long-term clogging processes associated with high HLR values and to the variability in outflow water quality at the same HLR, as shown in Fig. 5.

Table 4

Statistical analysis on the main VGS design parameters. Pot-and-pocket based systems are analysed separately from ground-based systems, to ensure comparability. The table reports mean values, standard deviation, minimum and maximum values, quartiles and the number of studies reporting each parameter.

Pot & Pocket-based VGS	Treatment area (level)	Treatment area (total)	VGS area vertical	Media volume (level)	n° levels	Depth (level)	Media weight	HLR (first level)	HLR	OLR (first level)	OLR	HRT	OCR	COD in	COD out	COD rem.	BOD$_5$ in	BOD$_5$ out	BOD$_5$ rem.
	m^2	m^2	m^2	m^3		m	kg m^{-2}	$Lm^{-2}d^{-1}$	$Lm^{-2}d^{-1}$	g $m^{-2}d^{-1}$	g $m^{-2}d^{-1}$	d	g $m^{-2}d^{-1}$	mg L^{-1}	mg L^{-1}	%	mg L^{-1}	mg L^{-1}	%
mean	0.77	3.30	10.18	0.23	3.7	38.48	36.54	498.24	150.96	204.93	40.36	1.43	31.38	300.4	86.5	72.2	101,5	8,16	88,0
st. dev.	1.87	6.36	20.35	0.34	2.5	111.26	25.60	1103.54	273.34	330.63	69.37	0.45	17.36	239.7	77.6	20.9	76,8	10,77	17,8
min	0.00	0.02	0.06	0.00	1.0	1.00	5.59	53.57	8.30	20.51	0.68	1.00	3.23	43.9	6.3	18.3	17,1	0,60	24,6
1Q	0.04	0.11	0.28	0.02	3.0	1.00	16.51	107.14	32.63	50.00	12.35	1.20	19.70	120.0	24.2	56.0	49,1	2,00	85,0
2Q	0.11	0.39	1.14	0.03	3.0	3.00	41.22	210.00	70.00	122.41	31.05	1.40	36.01	275.0	66.0	80.0	84,5	3,80	95,4
3Q	0.33	3.11	11.19	0.48	4.0	5.00	54.40	617.65	106.26	156.53	41.62	1.65	40.30	395.6	150.7	90.5	137,6	8,35	97,3
max	10.00	29.00	80.00	1.23	10.0	512.00	78.22	7500.00	1500.00	1923.75	384.75	1.90	67.94	928.0	268.0	96.6	307,0	41,50	99,0
n.	35	32.00	26.00	24	32.0	31.00	17	45		37	28	3	17.00	23	41	47	18	27	29
Ground-based VGS		**Treatment area (total)**	**VGS area**	**Media volume (level)**		**Depth (level)**			**HLR**		**OLR**			**COD in**	**COD Out**	**COD rem.**	**BOD$_5$ in**	**BOD$_5$ out**	**BOD$_5$ rem.**
		m^2	**m^2**	**m^3**		**m**			**L $m^{-2}d^{-1}$**		**g $m^{-2}d^{-1}$**			**mg L^{-1}**	**mg L^{-1}**	**%**	**mg L^{-1}**	**mg L^{-1}**	**%**
mean		14.53	248.33	5.74		0.70			102.83		31.60			328.3	23.3	93.2	130,0	8,00	92,3
st. dev.		20.25	128.19	6.75		0.12			49.59		25.53			46.9	13.5	3.9	53,0	5,62	2,0
min		0.11	105.00	0.09		0.60			73.00		11.40			260.0	10.0	86.0	69,0	5,00	88,5
1Q		2.78	196.50	0.70		0.60			79.25		17.85			319.3	14.0	92.0	112,5	5,00	92,8
2Q		5.31	288.00	3.19		0.70			85.00		23.10			343.5	16.0	94.0	156,0	5,00	92,8
3Q		17.46	320.00	9.28		0.80			91.50		36.84			352.5	27.0	96.0	160,5	8,00	92,8
max		53.00	352.00	16.80		0.80			203.00		68.80			366.0	49.0	97.3	69,0	5,00	92,8
n.		6	3	6		4			6		4			4	11	11	3	4	4

Table 5
Summary of preliminary design recommendations for pot and pocket-based VGS treating and reusing greywater.

Design parameter	Unit	Literature review Q1 – Q3[a]	Design indications direct reuse	Design indications treatment and reuse	Treatment wetland guidelines[b]
depth per level (from 1 to 15 levels)	cm	15 – 25	> 15 > 3 levels	15 > 3 levels	70 – 100
medium weight	$kg\ m^{-2}$	16 – 55			
HLR first level	$L\ m^{-2}\ d^{-1}$	107 – 620	N/A	Not recommended as design parameter	< 160 (VF sand 0.2 – 2.0 mm - greywater)
OLR first level	$g_{COD}\ m^{-2}\ d^{-1}$	50 – 157	N/A	< 40	< 20 (VF sand 0.2 – 2.0 mm - greywater)
HLR total	$L\ m^{-2}d^{-1}$	33 – 106	< 20	N/A	
OCR	$g_{O2}\ m^{-2}\ d^{-1}$	19 – 40[c]	N/A	< 20 (if VF)	30 (VF sand 0.2 – 2.0 mm)
HRT	d	1.2 – 1.65	N/A	> 1 (if HF)	To be verified by kinetic equations
COD removal	%	56 – 94	> 80	> 80	
COD conc. in	$mg\ L^{-1}$	120-396			
COD conc. out	$mg\ L^{-1}$	24 – 150	< 60	< 60	
BOD_5 removal	%	85 – 97	> 80	> 80	
BOD_5 conc. in	$mg\ L^{-1}$	50-138			
BOD_5 conc. out	$mg\ L^{-1}$	2.0 – 8.4	< 10	< 10	

[a] Full dataset in Annex, considering only pot-and-pocket-based VGS.
[b] Dotro et al. (2017); DWA 2017 (Nivala et., 2018).
[c] Calculated on COD.

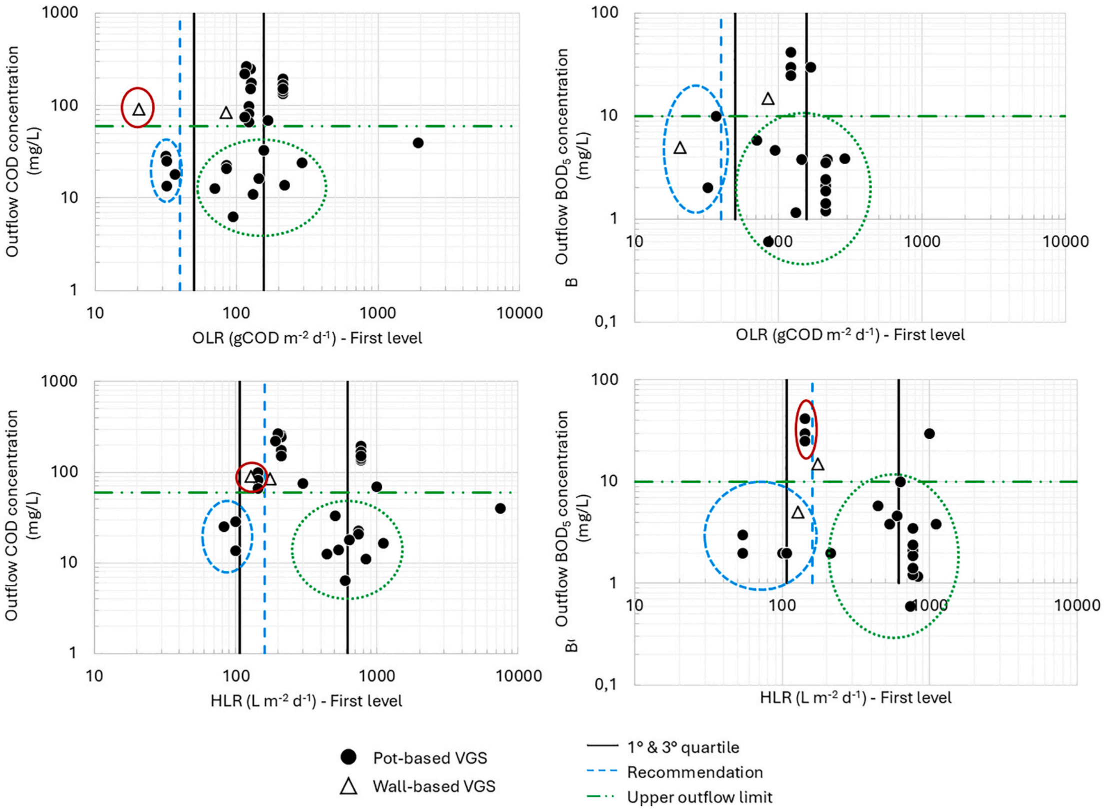

Fig. 5. Loading charts for VGS treating greywater. Outflow COD concentration (on the left) and BOD_5 concentration (on the right) on OLR (top)/HLR (bottom) at first level in pot and wall-based systems. Black continuous lines show the first and third quartiles, blue dashed line shows the maximum recommended value and the green horizontal line shows the upper limit of outflow concentration. Clusters of data: blue dashed, cases fulfilling the target upper flow limit, being below the recommended design value; green pointed, cases fulfilling the target upper flow limit, outperforming the recommended design value; red continuous, cases above the target upper flow limit, even if below the recommended design value.

Available data were insufficient to investigate potential effects of filling media on treatment performance, and available literature does not provide clear evidence on preferred lightweight media type and/or additives (Boano et al., 2021b; Costamagna et al., 2023; Sami et al., 2023), once a proper balance between coarse and fine media is ensured (Masi et al., 2016). Consequently, the design indications and expected performance reported in this section must be considered significant when filling media similar to those tested in literature are used (e.g., coco coir as fine material and expanded clay or perlite as coarse material). Details on the media used in the analysed studies are provided in the dataset in Supplementary online material.

Ground-based green façades for greywater treatment and reuse have been tested as conventional batch-fed VF wetlands planted with climbing species (Kotsia et al., 2020; Masi, 2025; Obeidat et al., 2025a; Stefanatou et al., 2024), particularly with respect to filling media (sand or gravel). For these systems, established design criteria and parameters for VF wetlands can be applied, including HLR values below 160 L m^{-2} d^{-1}, OLR below 20 g_{COD} m^{-2} d^{-1} and OCR around 30 gO_2 m^{-2} d^{-1}.

3.3.2. Green roofs

For the design of green roofs for greywater treatment and reuse, the main parameters identified from the literature review (Table 6) are substrate depth, structural weight, HLR, OLR and OCR. (full dataset in Supplementary online material). Similarly to VGS, Table 7 summarises the main statistical information derived from the literature review on green roofs treating greywater and presents the corresponding design indications according to the system purpose (i.e. direct use or treatment and reuse), in comparison with the established TW guidelines. Each design parameter is discussed, one by one, below, including the comparison with TW literature and the suggested guideline value for designing VGS.

Depth and associated structural weight depend on the intended use of the system. For direct greywater reuse for irrigation, design indications follow the principles of extensive green roofs, i.e. substrate depth >10 cm and total weight <100 kg m^{-2}. To enable the distribution of untreated greywater for the irrigation of the green roof, a slope of 10° is suggested (the Wetroof proposed by Zapater-Pereyra et al., 2016 has a slope of 14°). When the objective is to maximize the volume of treated greywater per unit roof area, design parameters follow recommendations for intensive green roofs, i.e. substrate depth >30 cm and total weight >300 kg m^{-2}. In this case, no slope is required.

As already observed for VGS, the OLR is also a key parameter to prevent clogging in green roofs treating greywater, especially when systems are designed for treatment and further reuse. Literature analysis shows a relatively narrow range of OLR values (Q1-Q3: 3.6 and 8.3 g_{COD} m^{-2}d^{-1}, Fig. 6). Given the still limited number of available studies, a conservative design value of OLR <4 g_{COD} m^{-2} d^{-1} is suggested, corresponding approximately to the Q1 of the observed data distribution. This cautious approach is considered appropriate at the current stage to minimise operational risks. It is worth noting that these values remain significantly lower than typical design guidelines for vertical subsurface flow treatment wetlands treating greywater (OLR< 20 g_{COD} m^{-2} d^{-1} for VF wetlands filled with coarse sand 0.2 – 2.0 mm and treating greywater – Nivala et al., 2018).

HLR values also depend on the intended use. When greywater is used only for irrigation, the suggested design value should not exceed 10 L m^{-2} d^{-1} (e.g. Zapater-Pereyra et al., 2016) and should be adapted to local climatic conditions, evapotranspiration potential and plan water demand. In the case an effluent should be generated for further use of treated greywater, the HLR is one of the possible design parameters to check the possible risk of clogging for long term operation. Literature analysis (Table 6) reports a quite wide range of values ranging between 4 and 70 L m^{-2} d^{-1} with the only exception of Liu et al. (2021), who presented HLR up to 100 L m^{-2} d^{-1}, and Masi (2025) and Masi et al. (2015) who used a design value of 170 L m^{-2} d^{-1}. However, we preferred to propose a conservative value in line with literature values tested for green roofs treating greywater, lower than 40 L m^{-2} d^{-1}(Fig. 6), even if significantly lower than design indication for vertical subsurface flow treatment wetlands (<160 L m^{-2} d^{-1} for VF TW filled with coarse sand 0.2 – 2.0 mm and treating greywater – Nivala et al., 2018).

Fig. 6 shows distinct performance clusters linking organic and hydraulic loading rates to effluent COD concentrations in green roofs treating greywater. Systems operating below the recommended first-level design thresholds (OLR <4 g_{COD} m^{-2} d^{-1}; HLR <40 L m^{-2} d^{-1}) generally achieve effluent COD concentrations below the upper outflow limit of 80 mg_{COD} L^{-1}, confirming the validity of these design indications. Nevertheless, the analysed datasets and graphical trends

Table 6
Statistical analysis on the main green roofs design parameters. The table reports mean values, standard deviation, minimum and maximum values, quartiles and the number of studies reporting each parameter.

Green roof	Area	Depth	Water level	Porosity	Media weight	Total weight (media + water)	HLR	OLR	HRT	OCR	COD in	COD out	COD removal	BOD$_5$ in	BOD$_5$ out	BOD$_5$ removal
	m^2	m	m	m^{3}m^{-3}	kg m^{-2}	kg m^{-2}	L m^{-2}d^{-1}	g m^{-2}d^{-1}	d	g m^{-2}d^{-1}	mg L^{-1}	m^2	mg L^{-1}	mg L-1	mg L-1	%
mean	25.22	0.24	0.23	0.36	189.42	274.16	34.82	8.60	2.74	11.12	310.1	61.1	72.9	121.4	36.3	71.3
st. dev.	81.04	0.13	0.14	0.06	202.62	254.06	34.51	10.55	2.34	14.44	199.4	47.4	26.4	78.9	27.9	20.0
min	0.28	0.09	0.10	0.26	28.20	88.20	3.75	0.04	0.54	1.01	81.5	5.2	−60.0	19.6	1.6	34.9
1Q	1.08	0.15	0.15	0.35	82.00	145.00	15.23	3.60	1.00	2.07	185.0	25.7	64.5	86.3	12.0	57.1
2Q	1.12	0.21	0.24	0.40	110.00	202.00	28.25	5.20	1.80	3.31	262.0	46.6	79.0	100.0	38.3	69.4
3Q	5.49	0.29	0.26	0.40	185.00	303.00	45.15	8.26	3.90	12.56	335.0	79.9	92.3	148.0	49.0	90.9
max	306.00	0.62	0.62	0.40	932.00	1180.00	173.91	48.35	8.00	48.28	754.0	230.0	98.9	285.0	86.0	97.0
n.	14	18	14	15	21	19	28	29	15	57	17	61	63	11	25	25

Table 7
Summary of preliminary design recommendations for green roofs treating and reusing greywater.

Design parameter	Unit	Literature review Q1 – Q3[a]	Design indications direct reuse	Design indications treat and reuse	Treatment wetland guidelines[b]
depth	cm	15 – 29	> 10	> 30	70 - 100
medium weight	kg m^{-2}	82 – 185	< 100	> 200	
total weight (including water)	kg m^{-2}	145 – 303	< 150	> 300	
HLR	L m^{-2} d^{-1}	15 – 45	< 10	< 40	< 160 (VF sand 0.2 – 2.0 mm - greywater)
OLR	g_{COD} m^{-2} d^{-1}	3.6 – 8.3	N/A	< 4	< 20 (VF sand 0.2 – 2.0 mm - greywater)
HRT	d	1.0 – 3.9	N/A	> 1 (if HF)	To be verified by kinetic equations
OCR	g_{O2} m^{-2} d^{-1}	2.1 – 13[c]	N/A	< 10[c]	up to 10 for HF 30 for VF (sand 0.2 – 2.0 mm)
COD removal	%	65 – 93	> 90	> 70	
COD conc. in	mg L^{-1}	185-335			
COD conc. out	mg L^{-1}	26 – 80	< 40	< 80	

[a] Full dataset in Annex.
[b] Dotro et al. (2017); DWA 2017 (Nivala et., 2018); Nivala et al. (2013).
[c] Calculated on COD.

indicate that higher OLRs, potentially up to 5–6 g_{COD} m^{-2} d^{-1}, may be feasible under suitable design and operational conditions, since several systems maintain compliant effluent quality at higher OLRs, indicating a degree of operational robustness.

Underperforming cases, characterized by effluent COD concentrations exceeding 80 mg COD L^{-1}, are limited when OLR is used as the primary design indicator. In contrast, exceedances are more frequent when hydraulic loading rate is considered, with multiple systems exceeding the COD threshold despite operating within the recommended HLR range. This indicates that OLR provides a more consistent predictor of treatment performance in green roofs, while HLR should not be used as a standalone design parameter.

If green roofs for greywater treatment are designed with a horizontal subsurface flow, HRT should be the main design parameter, and it should be similar to that used in HF wetlands. Based on the literature review, a minimum HRT of more than 1 day is recommended, with reported values ranging from 1.0 to 3.9 days. HF wetlands are rarely designed with an HRT value below 1 day, even when treating light greywater. Accordingly, the same design approach can be applied to green roofs, and the standard design equations developed for HF wetlands (Dotro et al., 2017) may support the dimensioning of such systems.

OCR can also be adopted as a design parameter for green roofs that treat and reuse greywater. Based on the literature, an OCR value greater than 10 gO_2 m^{-2} d^{-1} is recommended. This threshold falls within the range reported in existing studies (2–13 gO_2 m^{-2} d^{-1}) and is consistent with values typically applied to horizontal flow TW, which are the most common type of roof wetlands investigated so far (found in 8 out of 13 cases). If green roofs are designed to operate more similarly to VF wetlands, even higher OCR values may be appropriate, potentially up to 30 gO_2 m^{-2} d^{-1}, as suggested for VF wetlands (Dotro et al., 2017).

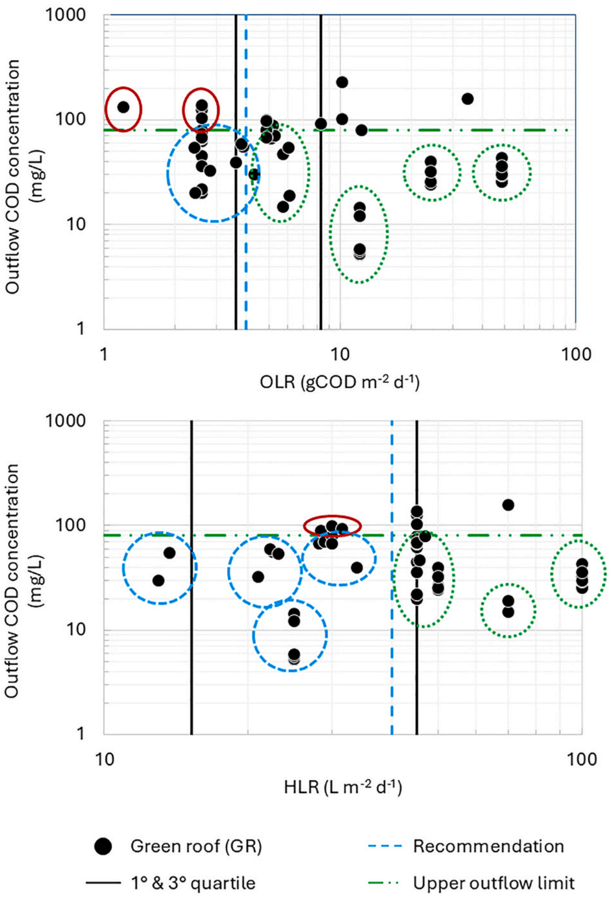

Fig. 6. Loading charts for green roofs treating greywater. Outflow COD concentration on OLR(top)/HLR(bottom) green roofs. Black continuous lines show the first and third quartiles, blue dashed line shows the maximum recommended value, and the green horizontal line shows the upper limit of outflow concentration. Clusters of data: blue dashed, cases fulfilling the target upper flow limit, being below the recommended design value; green pointed, cases fulfilling the target upper flow limit, outperforming the recommended design value; red continuous, cases above the target upper flow limit, even if below the recommended design value.

The statistical analysis suggests that, when the proposed design recommendations are applied, green roofs operating at lower HLR values and targeting direct reuse can achieve a high COD removal efficiency (>90%) and low effluent COD concentration (<40 mg L^{-1}) (Table 7). When systems are designed to treat and reuse greywater at higher HLR values, a probable reduction in performance can be expected (COD removal >70% and effluent COD concentration <80 mg L^{-1}), see Fig. 6.

Available data were insufficient to assess the influence of filling media on treatment performance in detail, and the available literature does not provide clear evidence on preferred lightweight media type and/or additives once appropriate depth and HLR values are ensured (Thomaidi et al., 2022). Therefore, the design indications and expected performance reported in this section must be considered significant when filling media similar to those tested in the literature are used (e.g., expanded clay). Filling media used in the analysed studies is provided in the Supplementary online material dataset. Further research is still needed to achieve higher and more stable treatment performance in green roofs treating greywater. In particular, the use of mixed lightweight media, similar to those investigated for green walls (e.g. coco coir combined with expanded clay or perlite) and tested under vertical flow batch mode, represents a promising research direction, exploring the possibility to test higher HLR and OLR values in green roofs for greywater treatment and reuse.

4. Conclusion

In line with SDG11 (Sustainable Cities and Communities) and SDG6 (Clean Water and Sanitation), urban areas are increasingly adopting green strategies to face climate change impacts on water security while delivering multiple co-benefits. Among different NbS developed for greywater management, green walls and green roofs are particularly suitable for dense urban areas, as they exploit vertical surfaces and rooftops without requiring additional land consumption. In this emerging field, this study analysed peer-reviewed literature and documented best practices to develop a structured set of recommendations providing clear quantitative design indications to facilitate both green walls and green roofs applications for greywater treatment and potential reuse.

Key design parameters such as system depth, HLR, OLR, HRT and OCR were defined and discussed for both technologies. Recommended value ranges and design criteria were derived from statistical analysis of available case studies and linked to target removal performances for both BOD_5 and COD. Different implementation schemes were considered in the statistical analysis of existing case studies, to support flexible, tailor-made design solutions, in line with the well-established field of treatment wetlands.

Future perspectives seem similar among green walls and green roofs, most likely confirming greywater as one of the most promising non-conventional water resources to unlock the potential of these technologies in future cities. In this path, further research should focus on three main aspects: (i) investigate the correlation between the multiple co-benefits that characterize these solutions (e.g. urban heat island reduction, air quality improvement, building insulation, property economical value, health benefits, aesthetic), supporting their development with a solid monitoring data on multifunctionality; (ii) stabilizing and improving treatment performances through a deeper comprehension of the specific contribution and impact of different materials (e.g. growing media mix and plant species), accordingly to the selected structure design; (iii) identifying and testing materials and configurations that can limit the overall costs of these NbS to improve their benefit-cost ratio and foster their implementation.

CRediT authorship contribution statement

A. Rizzo: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **C. Sarti:** Writing – review & editing, Investigation, Data curation. **F. Masi:** Writing – review & editing, Methodology, Funding acquisition, Formal analysis, Conceptualization. **E. Costamagna:** Writing – review & editing, Writing – original draft, Formal analysis. **F. Boano:** Writing – review & editing, Writing – original draft, Funding acquisition, Formal analysis. **B. Pucher:** Writing – review & editing, Writing – original draft, Formal analysis.

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.

Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation program NICE under grant agreement No 101003765.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.129928.

Data availability

Full dataset is available in Excel format as online supplementary material.

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