

Vertical greening systems for greywater treatment

Disclaimer: the following text provides a condensed summary of Chapter 17, *Vertical Greening Systems for Greywater Treatment*, by Bernhard Pucher, Elisa Costamagna and Fulvio Boano, published in 2025 in the Elsevier book *Emerging Developments in Constructed Wetlands* (pp. 399–422). The summary outlines the main concepts, technical characteristics and findings presented in the original chapter, focusing on the application and performance of vertical greening systems for greywater treatment.

Introduction

Increasing urbanisation and climate change are placing growing pressure on cities, particularly on freshwater resources and wastewater management. Nature-based solutions (NBS) are gaining attention for their potential to mitigate urban environmental problems while supporting resource recovery and circular economy principles.

Treatment wetlands already exploit natural processes for wastewater treatment, but their land requirements limit their integration into densely built environments. Vertical greening systems (VGS) offer an alternative by combining building-integrated vegetation with wastewater treatment while requiring limited horizontal space.

However, urban greening also increases irrigation demand. Greywater represents a potential alternative to freshwater, allowing VGS to combine irrigation, wastewater treatment and water reuse. Despite their potential, existing studies differ considerably in system design, operating conditions and treatment performance.

VGS as treatment wetlands

Vertical greening systems (VGS) are classified into three main categories: ground-based, wall-based and pot-based green façades. Ground-based systems use climbing vegetation rooted in soil or containers, while wall-based systems incorporate growing media into panels or supporting structures attached to façades. Pot-based systems consist of individual pots or planters, generally filled with soilless substrates and supported by the building.

Pot-based systems are the most widely investigated configuration for greywater treatment, while wall-based and ground-based alternatives have received less attention. Their modular arrangement allows water to pass through successive treatment units, increasing contact with the growing media despite the limited space available.

VGS can combine greywater treatment with irrigation, reducing freshwater demand while potentially producing treated effluent for further reuse. Their treatment processes are comparable to those occurring in constructed wetlands, including sedimentation, filtration, adsorption and biological degradation. The growing media play an important role in pollutant removal, while treatment efficiency also depends on hydraulic and organic loading rates (HLR and OLR), feeding intervals and substrate hydraulic properties. As they combine vegetation, saturated or variably saturated conditions and pollutant removal, VGS can be considered a subcategory of treatment wetlands.

Application of VGS for wastewater treatment

The use of greywater in vertical greening systems (VGS) can follow two main approaches: direct irrigation with untreated greywater or treatment aimed at producing an effluent suitable for further reuse. The latter requires specific design and operating conditions to ensure adequate pollutant removal. Although other wastewater sources have been investigated, most research focuses on greywater because of the potential health risks associated with wastewater use in urban environments.

Most studies have investigated pot-based systems, generally consisting of multiple containers connected vertically in series, sometimes with parallel distribution lines. This arrangement compensates for the limited substrate volume available in VGS compared with conventional treatment wetlands. Systems vary considerably in size and configuration, ranging from laboratory-scale experiments to larger pilot installations. Vertical flow is the most common arrangement, particularly in small pots, while horizontal flow is generally adopted in larger planter boxes.

The selection of plant growing media (PGM) is essential for both hydraulic behaviour and treatment performance. Lightweight inorganic materials, such as expanded clay, perlite and zeolite, are commonly combined with organic components, particularly coconut fibre, to reduce structural loads while providing suitable conditions for filtration and pollutant removal. Some materials can also enhance the adsorption of specific pollutants, including ammonium and phosphorus. However, no standardised guidelines for PGM selection are currently available, and clogging remains a significant concern, influenced by both substrate characteristics and operating conditions.

Unlike conventional treatment wetlands, VGS can accommodate a wide variety of ornamental plants, selected according to climatic conditions, substrate properties and available space. Besides providing shading, cooling and other environmental benefits, vegetation can contribute to nutrient removal. However, pollutant uptake does not necessarily represent permanent

removal unless plant biomass is harvested. Experimental studies have shown that plant species can influence nutrient removal, although differences in organic matter removal are not always significant. Long-term plant development can also increase the risk of clogging through root growth.

Operational conditions differ substantially among the investigated systems. Total substrate surface areas range from 0.12 to 27 m², with arrangements typically comprising three to six levels. Hydraulic loading rates (HLR) applied to the uppermost treatment level range from approximately 83 to 1,000 L m⁻² d⁻¹, while organic loading rates (OLR) range from 8 to 204 g COD m⁻² d⁻¹. These differences are not directly related to system size and reflect the absence of established design criteria. Greywater is generally supplied intermittently, using short feeding events to maintain aerobic conditions within the growing media. The considerable variability in system configurations, loading conditions and feeding schedules highlights the need for more consistent design and operational guidelines.

Greywater treatment performance

Research on greywater treatment in vertical greening systems (VGS) has considered both real and synthetic greywater, with only a limited number of studies using wastewater collected from actual buildings. Treatment performance is generally assessed through physical and chemical parameters, including organic matter, suspended solids, nitrogen, phosphorus and micropollutants. Removal efficiency depends on the characteristics of the incoming greywater, growing media composition and operating conditions.

Pollutant removal relies on several physical, chemical and biological processes. Suspended solids are mainly retained through sedimentation and filtration, making pre-treatment important to prevent clogging. Organic matter is removed through physical retention and microbial degradation, while nitrogen transformation depends on oxygen availability. Aerobic conditions favour nitrification, whereas denitrification requires anoxic conditions. Intermittent feeding generally promotes aerobic conditions in vertical-flow systems, although saturated drainage layers can support anoxic processes. Phosphorus is primarily retained through adsorption and precipitation, while plant uptake can contribute to nutrient removal. However, nutrient accumulation in vegetation does not necessarily represent permanent removal unless the biomass is harvested.

Regarding physical parameters, VGS generally stabilise pH around neutral or slightly alkaline values, while electrical conductivity is only moderately affected by treatment. In contrast, turbidity removal is particularly effective, commonly reaching 95–97%. This performance is mainly associated with the filtration capacity of the growing media.

Organic matter removal is generally high, with reported efficiencies ranging from 43% to 96%. Although influent concentrations vary considerably, removal efficiency does not appear to be directly related to the initial organic matter concentration. Organic loading rate (OLR), hydraulic loading rate (HLR) and feeding conditions have a greater influence on performance. Higher organic loads may reduce treatment efficiency and infiltration capacity, particularly in systems with limited substrate volumes. Long-term investigations have also identified declining performance and clogging associated with root development and substrate characteristics, highlighting the importance of appropriate design and operational management.

Nitrogen removal mainly involves microbial nitrification and denitrification, although plant uptake and adsorption can also contribute. Zeolite-containing substrates can enhance ammonium retention, potentially supporting subsequent biological transformation. Temperature and hydraulic loading conditions significantly influence nitrogen removal, as lower temperatures reduce microbial activity while longer retention times can improve treatment. Reported total nitrogen removal efficiencies range from 70% to 99%, although the relative importance of biological processes and plant uptake varies among studies.

Phosphorus removal occurs mainly through adsorption, complexation and precipitation within the growing media, together with uptake by plants and microorganisms. Reported removal efficiencies range from 24% to 52%. However, adsorption capacity is limited, and substrate saturation can progressively reduce phosphorus retention or cause its release into the effluent. Plant growth may increase phosphorus uptake over time, but the available experimental periods are insufficient to establish long-term treatment performance.

Micropollutants represent an additional concern because of their potential environmental and health risks, particularly when treated greywater is intended for reuse. Although research remains limited, investigations have demonstrated the potential of growing media such as coconut coir, zeolite and perlite to remove xenobiotic organic compounds. A study examining 26 micropollutants in a VGS treating real greywater reported removal efficiencies between 28% and 99.9%, with 14 substances achieving removal above 90%.

Overall, VGS demonstrate considerable potential for removing organic matter, suspended solids, nutrients and selected micropollutants from greywater. However, treatment performance varies among systems, and uncertainties remain regarding long-term efficiency, substrate saturation and clogging. These limitations highlight the need for further investigations into the influence of system design, operating conditions and long-term pollutant removal mechanisms.

Synthesis and recommendations for future VGS research

The studies reviewed demonstrate the potential of vertical greening systems (VGS) for removing organic pollutants and nutrients from greywater. Treatment performance depends on system design, plant growing media (PGM), vegetation and operational conditions, particularly hydraulic and organic loading rates (HLR and OLR) and feeding intervals. Although different substrates have generally achieved comparable treatment performances, their hydraulic properties and interactions with operating conditions remain important for ensuring long-term efficiency and preventing clogging.

The considerable variability in system configurations, dimensions and operating conditions highlights the need for standardised design criteria and reporting procedures. Future studies should provide detailed information on system geometry, PGM composition and properties, vegetation, wastewater characteristics and flow configurations. Operational parameters, including HLR, OLR, feeding frequency and applied volumes, should be consistently reported, together with influent and effluent pollutant concentrations, sampling procedures and experimental duration.

Further long-term investigations are needed to assess treatment stability, substrate saturation and clogging under real-world conditions. More consistent experimental methods and reporting standards would facilitate comparisons between studies and support the development of reliable guidelines for designing VGS capable of achieving the required effluent quality for water reuse.