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Review

Greywater Phytoremediation in Building-Integrated Greenery Systems: A Review

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Abstract

Global water scarcity is mainly due to climate change, population growth, excessive use of water resources and inadequate water management. Alternative sources such as reusing greywater are promising in urban environments. In this context, phytoremediation, the direct use of plants to remove soil and water pollution, could be an encouraging alternative nature-based solution to traditional reuse methods. While constructed wetlands are the most common method for greywater phytoremediation, their limited feasibility in cities makes green roofs and walls a practical urban alternative. This review examines studies conducted over the last 20 years. The combination of greywater treatment through phytoremediation with urban greenery would help close the water cycle as well as make cities more sustainable. However, for this solution to be viable, several challenges must be addressed, including limited roof or wall surface area compared to traditional systems, the precise volume of water to be managed, and the selection of suitable substrates and plants essential for effective phytoremediation. This work reviews the main mechanisms and factors that drive the phytoremediation process in constructed wetlands, and based on this knowledge, delves into the challenges of applying this process to the urban context through green roofs and facades on buildings.

Keywords: building-integrated greenery; constructed wetlands; phytoremediation; green roofs; green walls; greywater

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1. Introduction

Climate change has been a major concern throughout the years. Its effects are increasing. Its forecasts predict more droughts and inconsistency in precipitation, affecting water resource availability [1–5]. It threatens water security by altering precipitation and other climatic factors, potentially impacting water supplies in various places [6]. For instance, further strain will be anticipated on some basins' water balance due to declining precipitation and rising temperatures [7,8]. Climate change and socio-economic growth impact agricultural water consumption, resulting in water shortages [9,10]. However, there is consensus on a general warming trend due to climate change. The magnitude and timing of warming and the consequences on localized systems requiring adaptation options remain unclear [11]. Ecomimetic design (ED) and nature-based solutions (NBS) are potential ways to mitigate climate change. ED and NBS recreate aspects of natural systems to merge ecosystem services into the human environment, building up the effective use of natural

assets, human well-being, and integrated green growth. NBS can be a sustainable solution for decentralizing wastewater treatment and mitigating climate change [12].

Rapid resource exploitation results from the expanding economy and population as well as the proliferation of consumeristic urban lifestyles. In fact, the trend of population concentration known as "urbanization" is a major cause of numerous environmental problems. It influences energy and water consumption in families and industries [13]. Population density and industrial zones have led to increased demand for water sources. At the urban scale, this demand exceeded the supply [14]. Thus, there is a need for a sustainable approach to water resource management [15]. The issues of urban water management and water shortages underline the importance of the transition to water circularity and present an opportunity for incorporating NBS in cities [16,17]. Integrating NBS into circular water systems offers benefits such as providing an alternative water source, enhancing urban water security, minimizing freshwater demand, and assisting cities in managing stormwater, wastewater, and integrated sewer overflows [18]. In fact, one of the main challenges in creating sustainable cities is the replacement of vegetated areas with hard surfaces that store more heat and alter the urban microclimate, due to urban densification in recent decades [19].

Reusing greywater from buildings could be of vital importance. It helps reduce urban water shortages at household and commercial buildings and can enhance urban sustainability [20–22]. Moreover, decentralized source-separated wastewater treatment systems are a viable alternative to traditional centralized systems in certain zones [22,23]. In addition, incorporating food production within urban areas could help in achieving effective final wastewater treatment in cities [24].

Among the different greywater reuse strategies, those based on natural processes are more interesting in terms of sustainable construction and circular economy. Furthermore, constructed wetlands (CW) are a good choice for reusing greywater [25,26]. Greywater could be cleaned and reused through these lands, constituting the phytoremediation process. This phenomenon is discussed in detail in Section 3.

However, applying CW in urban environments is not feasible for many reasons, such as the vast amount of land required, hydrological and infrastructure limitations, and high land costs. Thus, implementing greenery in the building envelope (green roofs: GRs and green walls: GWs) is attracting attention for greywater recycling. Life Cycle Impact Assessment (LCIA) results show that the green roof water recycling system (GROW) outperformed other treatment technologies in most impact assessment areas [27]. Greywater is an effective alternative to fresh water for cleaning and watering activities, particularly in water-scarce countries. GRs offer multiple benefits, including wastewater treatment and greywater recycling. In addition, they act as a biofilter, refining water through physical, chemical, and microbial processes [28].

On the other hand, in light of previous studies, there is still a huge gap in research on adapting the phytoremediation process in building-integrated greenery (BIG) systems such as GRs and GWs. Most of the research on this topic is focused on CWs.

Moving from CWs to urban ones (Figure 1) is critical due to the different conditions in each one of them. For instance, the former is formed in large open areas, while the latter is limited to a building in an urban area (Figure 2). Therefore, the phytoremediation process in both areas is the same but with distinct constraints.

The main objective of this review is to determine the pending challenges that future research must face in order to make the use of BIG systems, mainly GRs and GWs, for graywater reuse in buildings viable. These obstacles could be listed as follows: delays in phytoremediation (nutrient and heavy metals availability, soil/substrate composition and depth, plant type, salinity), Hydraulic Loading Rate (HLR), Dissolved Oxygen content (DO),

Microplastics (MP) removal, as well as growth and biomass issues. In this work, we have explored the challenges that must be faced to use GRs and GWs for the reuse of greywater in buildings, and thus subsequently establish future lines of research in this area. Thus, first of all, the mechanisms and factors that drive the phytoremediation process have been reviewed in depth. Then, the main characteristics of urban wetlands and their operation have been reviewed, in order to adapt them to the specific conditions of GRs and facades. Finally, the previous research carried out on phytoremediation on GRs and facades has been reviewed. New emerging concepts such as "wetwall" have also been reviewed.

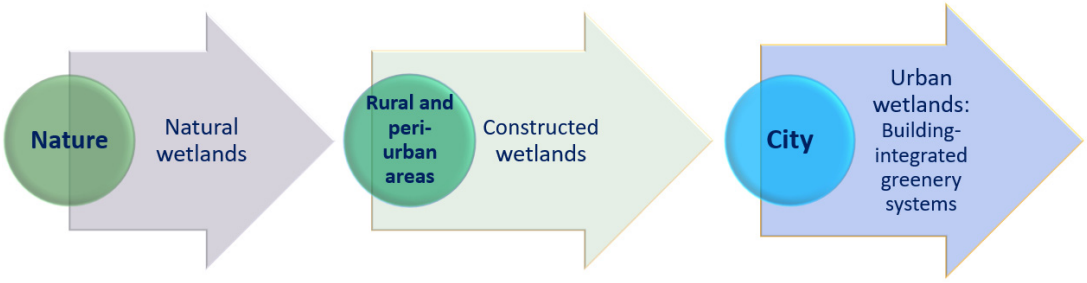
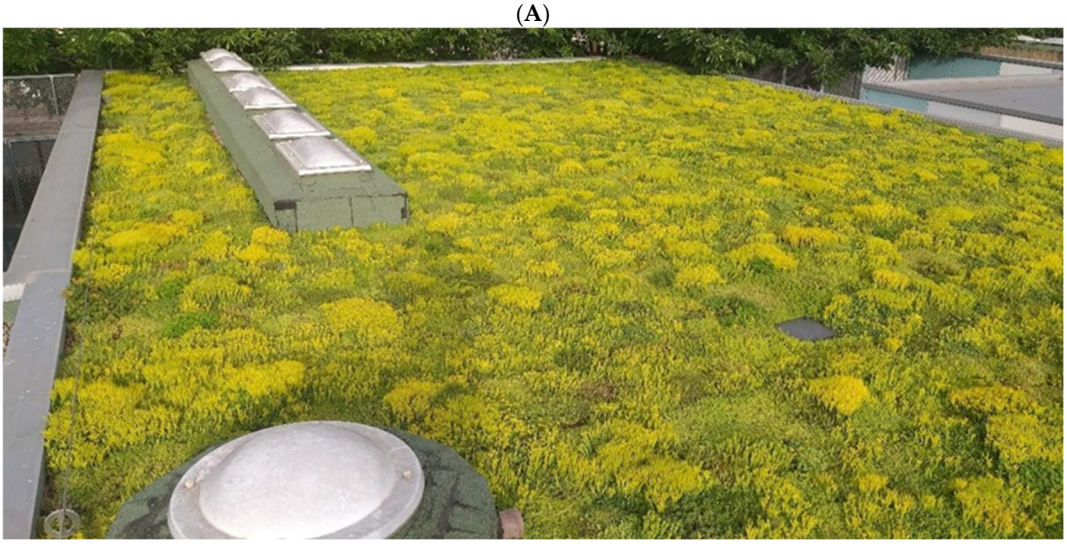


Figure 1. Conceptual progression of phytoremediation systems from natural ecosystems to urban applications.



(**A**)



(**B**)

Figure 2. Examples of Constructed Wetland (**A**) and Extensive Green Roof (**B**) in Lleida, Spain.

2. Methodology

Criteria for Selecting Literature and Its Classification

This review examined studies undertaken during the last 20 years. This timeframe was selected to catch the most recent and relevant advances in phytoremediation and urban

NBS, reflecting current scientific understanding and technological developments in the field. The research tool Web of Science was used to find these articles. Figure 3 shows four specific searches: phytoremediation AND constructed wetlands, phytoremediation AND green roofs and phytoremediation AND green walls. A total of 1776 articles were obtained. Thus, these records were screened based on the title, abstract, and keywords in order to avoid repetitions. In addition, the number of existing citations was taken into consideration.

The appropriate literature was sourced using the Mendeley reference manager. The following keywords were used to determine the literature: phytoremediation, constructed wetlands, green roofs, green walls, and greywater.

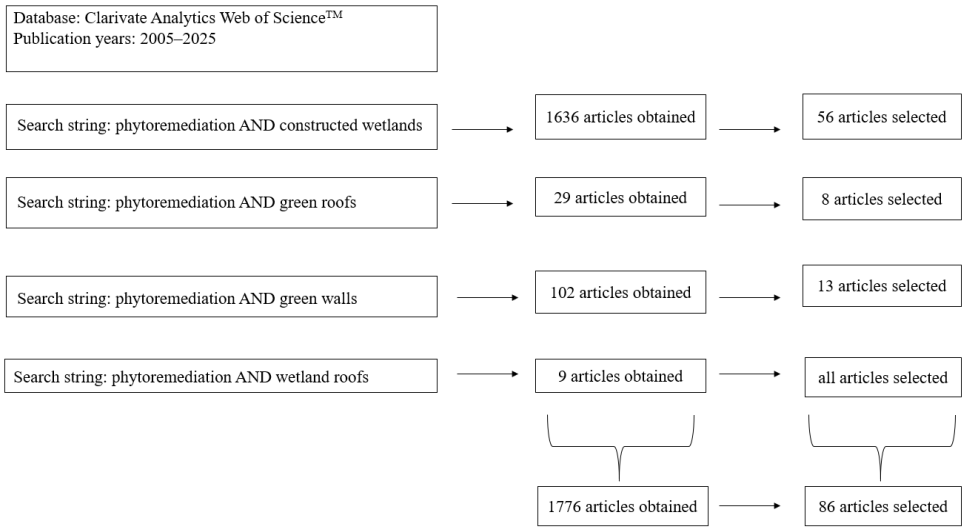


Figure 3. Scheme of the literature selection.

The literature linked to the phytoremediation strategies is divided depending on the types of NBS: CWs, GWS, and GRs.

3. Results and Discussion

3.1. Phytoremediation: The Process and the Mechanisms

The phytoremediation process is complex. In order to use it in BIG systems, it is necessary to know how it takes place and what the mechanisms are that make it possible.

The direct use of plants and associated microbes found in soil to minimize pollution and contamination of both soil and water is known as phytoremediation [29–33]. The application of sophisticated and specialized equipment is not necessary for phytoremediation. It is a practical, affordable, socially acceptable, efficient, non-invasive, and ecological substitute for physical remediation techniques that disrupt the ecosystem [34].

Phytoremediation can be applied to military, agricultural, industrial, mine, and wood treatment sites, as well as sewage and municipal wastewater, agricultural runoff, industrial wastewater, coal pile runoff, landfill leachate, mine drainage, groundwater plumes, and indoor and outdoor air [35].

The phytoremediation process is made up of seven distinct plant-based mechanisms, which take place in both the aerial part and the root part: phytostabilization, phytovolatilization, phytoextraction, phytodegradation, phytodesalination, rhizofiltration, and rhizodegradation.

Phytostabilization employs plants to stabilize contaminated soil rather than actively cleaning it [29]. The phytostabilization process does not require eliminating trace elements. There is less risk to the environment because they are instead kept in the soil by adsorption on the root surface, precipitation in the rhizosphere, or absorption and accumulation in the roots [34]. This mechanism prevents pollutants from migrating into groundwater or

air. Plants suitable for phytostabilization at a specific site should be tolerant to high levels of contaminants, produce high root biomass capable of immobilizing contaminants via uptake, precipitation, or reduction, and retain pollutants in roots rather than shoots to avoid certain handling and disposition of shoots [36].

The process of phytovolatilization entails pollutants being absorbed by plants, transpiring, and then evaporating in a changed form [34]. Unlike other remediation approaches, volatilization removes contaminants but does not limit their movement to adjacent regions. Phytovolatilization must be avoided in areas with high population density or peculiar weather circumstances that cause fast deposition of volatile chemicals [36].

Phytoextraction, or phytoaccumulation, involves drawing contaminants from soil and water and storing them in their aboveground biomass [34,37]. The hyperaccumulator plants, with a translocation factor (TF) and a bioconcentration factor (BCF) larger than 1, are a distinct group of over 400 species spread across 45 families. These plant kinds can help to clean up polluted soil by adsorption, transport and translocation, hyperaccumulation or transformation, and mineralization [29]. It is important to note that this mechanism has been proven to effectively eliminate TEs from the soil with vegetation such as *Zea mays*, *Nicotiana tabacum*, *Helianthus annuus*, and *Cannabis sativa*. Additionally, *Trifolium alexandrinum* is a decent plant that can catch zinc, copper, lead, and mercury [34].

The type of metal species greatly influences plant phytoextraction in the growing medium. Since most of the metals present are insoluble molecules that plants cannot absorb, only a minority of these metals are accessible for plant use. Heavy metals and metalloids are classified into three groups based on soil bioavailability: widely available (As, Cd, Cu, Ni, Se, and Zn); moderately available (Co, Fe, and Mn); and slightly available (Cr, Pb, and U) [29]. Phytoextraction uses a variety of plant species—particularly fast-growing, deeply rooted ones like Invasive Plant Species—to remove harmful heavy metals from the environment [38]. Phytoextraction is the primary and most effective phytoremediation method for removing heavy metals and metalloids from contaminated soils, sediments, or water [39].

Phytodegradation occurs within plant tissue, breaking down pollutants through metabolic mechanisms [40]. This mechanism involves specific enzymes responsible for degrading or mineralizing organic pollutants [41]. This method successfully eliminates moderately hydrophobic organic contaminants from shallow depths, including toluene, benzene, xylene, and ethylbenzene, chlorinated solvents, and short-chain aliphatic hydrocarbons [42].

Phytodesalination is carried out by halophytic plants, which are well adapted to tolerate heavy metals. Bassia indica, an annual halophyte with unique salt tolerance characteristics, can potentially decrease salinity in wastewater [39].

Rhizofiltration enhances the polluted water quality by adsorbing, concentrating, and precipitating contaminants using hydroponically produced plant roots [29]. The rhizofiltration process depends on the chosen plant species' roots' capacity to absorb and adsorb contaminants from surface and ground waters, as well as from municipal, industrial, and agricultural wastewaters and acid mine water [34]. Aquatic organisms such as water hyacinth, pennywort, and duckweed may remove heavy metals from water. Nevertheless, plants with tiny, slow-growing roots have restricted potential for rhizofiltration due to their inefficiency in extracting metals [36].

Rhizodegradation involves microorganisms' enzymatic breakdown of contaminants in soil [40]. In other words, bacteria degrade organic xenobiotics in the rhizosphere [39]. Dehalogenase, peroxidase, oxidoreductase, and dehydrogenase are the enzymes that use this technique [38].

Phytoremediation has been successfully applied to clean up soils contaminated by heavy metals, hydrocarbons, persistent organic compounds, volatile organic compounds, and other pollutants. Furthermore, this technology is used to remediate groundwater and surface water, including contaminated coastal areas where salinity-tolerant halophytic plants are used [34]. Its use in the removal of greywater from buildings is highly interesting from a sustainability perspective, as it is a natural process that addresses the problem of water shortages in the built environment.

Among these mechanisms, four occur in green roofs. For instance, phytoextraction of heavy metals (Pb, Cd and Zn) takes place where they are taken up into harvestable plant shoots [43]. Phytostabilization of heavy metals occurs where they are immobilized in the root area to prevent leaching [34]. Rhizodegradation of hydrocarbons and pesticides happens through microbial breakdown facilitated by root exudates [44]. Rhizofiltration of dissolved metals and nutrients occurs as well via adsorption from runoff water by root systems [34].

3.2. Factors Influencing the Phytoremediation Process

When reviewing previous work on the use of phytoremediation to recover greywater, a series of factors that influence the development of this natural process can be cataloged. Any attempt to manage the process in a directed manner in an artificial environment must consider the control of these factors and drivers. Factors and drivers influencing the phytoremediation process, as well as their impacts, are listed in Table 1. They include some delayers/accelerators, HLR, DO, MP capacity, plant growth and biomass issues, among others [45,46].

Table 1. Factors of phytoremediation.

Drivers/Factors	Impact/Details	Reference
Delayers/accelerators of phytoremediation	Nutrient and heavy metal availability; Soil/Substrate composition and depth; Plant type, salinity, pH, temperature	[47,48]
HLR	Optimal HLR in Mobile CW: 1.1 $m^3m^{-2}d^{-1}$; Lower HLR and higher hydraulic retention time (HRT) enhance heavy metal removal	[49,50]
DO	Critical for heavy metal elimination in fill-and-drain techniques	[50]
MP Removal	Smaller HLR improves MP removal; Using low-porosity filler materials enhances efficiency	[51]
Economic and Spatial Challenges	Land-use rescheduling increases costs; Limited root system depth reduces contamination reach	[52]
Plant Growth and Biomass Issues	Hyperaccumulator species grow slowly and have low biomass output, limiting phytoremediation efficiency	[40,52]
Techniques to Enhance Efficiency	Microorganism-plant interaction; Nutrient amendments (e.g., N and Zn fertilizers for Cd absorption); Genetic modifications and transgenic approaches for improved growth and biofortification	[53]

It is imperative to know this set of drivers and factors, as they must be appropriately controlled and managed if the phytoremediation process is to be used in artificial urban environments, and specifically in building-integrated greenery systems, such as GRs and

GWs. Thus, in order to regulate the phytoremediation process in any NBS, some critical factors must be taken into account, as illustrated in Figure 4.

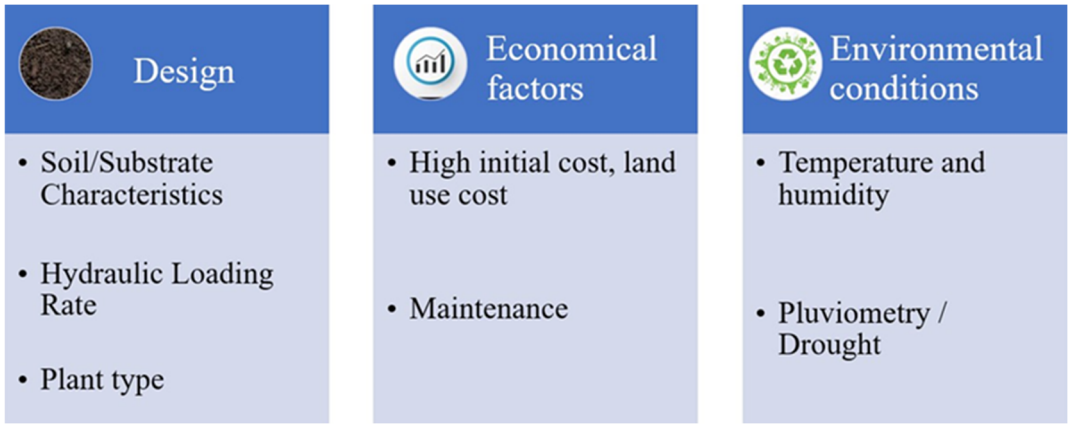


Figure 4. Critical factors affecting phytoremediation.

Soil or substrate properties could be considered the most effective factors of phytoremediation. Composition and depth of soil or substrate, as well as salinity and pH, are among these factors. For instance, an unsuitable soil or substrate can slow plant growth and contaminant uptake. Economic factors such as the costs related to the initial investment and land use are also affecting this process. Moreover, environmental circumstances like temperature, drought, plants and humidity must be taken into account.

3.3. Benefits of Phytoremediation

The phytoremediation process is considered one of the bioremediation processes, consisting of using nature-based solutions to reduce water, air, and soil pollution [54]. It provides several benefits listed below:

Environmental Benefits:

Pollutant removal from water and soils: It accumulates and removes contaminants effectively and applies to various contaminants [40]. It removes trace elements from ecosystems, mitigates environmental pollution, and treats heavy metals in contaminated water. All of these actions occur through biophysical and biochemical processes including translocation, absorption, transportation, acclimation, hyperaccumulation, and mineralization [55,56].

Biodiversity support: It makes it possible to provide animal habitat [57].

Climate regulation: It helps in sequestering carbon, leading to a mitigation of climate change [57].

Economic Benefits:

Cost and Sustainability: It is a low-cost and ecologically acceptable process [40] that does not alter the biological and physical characteristics of soil/substrate and is feasible for long-term application [55]. It is effective for broad land areas with minimal monitoring required [54].

Aesthetic Benefit: It gives the treated land a better landscape by planting vegetation [48,58].

Despite the mention of these benefits, a few drawbacks could exist, such as the huge area of land needed as well as possible odors resulting from the phytoremediation process.

3.4. Greywater Phytoremediation Solutions

Natural greywater treatment systems offer a sustainable solution for wastewater management [59]. CW is a green wastewater treatment technique that simulates existing

wetlands. It is a cost-effective, low-maintenance, and energy-efficient alternative to traditional wastewater treatment technologies [60,61]. The fundamental concept of treating wastewater in CWs relies on the root zone treatment system [62]. The literature is abundant, with studies indicating that plants play a beneficial role in eliminating pollutants in CWs [63].

The use of the phytoremediation process for reusing greywater in the urban context is still a pending challenge. Some previous initiatives have been addressed in different ways and to a greater or lesser extent, depending on the adopted construction solution. Three main typologies of solutions have emerged from the reviewed articles: CWs [64], GRs [65], and GWs [66]. Recently, the concept of "Wetwall" [12] has been developed as an evolution of the last two typologies, which could be framed within the concept of "Urban Wetlands" in contrast to CWs. According to the reviewed literature, in the urban context, the process of phytoremediation generally occurs in CWs [67]. Furthermore, 83% out of 86 papers reviewed were applied on CWs, whereas only 17% were related to BIG systems, specifically 9% on GR and 8% on GW. The fact that 17% of previous work focuses on the application of phytoremediation through building-integrated greenery systems highlights the growing interest in these NBS integrated into building skins. Reusing greywater in buildings is a very interesting strategy from the point of view of sustainable construction, although it is not without technical and acceptance challenges that must be faced. This article aims to review these challenges and propose future research paths.

3.4.1. Constructed Wetlands

CWs are man-made systems designed to mimic the ecological functions of natural wetlands. They consist primarily of soils, water, microorganisms, and vegetation [68]. They use natural processes to clean contaminated water through four mechanisms: UV irradiation, sedimentation, nutrient uptake, and microbial action [69–71]. Concerning their classification, Figure 5 illustrates it through a scheme. It is seen that traditionally CWs for wastewater treatment are divided into two groups based on their hydrology: free water surface (FWS) CWs and subsurface flow (SSF) CWs [72]. In FWS systems, wastewater flows shallowly over saturated substrates, similar to natural wetlands. In SSF systems, wastewater flows horizontally or vertically through the substrate, promoting plant growth. SSF CWs are classified as vertical flow (VF) or horizontal flow (HF) CWs based on flow direction. On the other hand, Hybrid CWs use a combination of wetland systems, including VF-HF, HF-VF, HF-FWS, and FWS-HF, to treat wastewater. Furthermore, multi-step CWs that included over three stages were utilized. Recently, to enhance the elimination processes of CWs, improved ones like artificially aerated CWs, baffled flow CWs, hybrid tower CWs, step feeding CWs, and circular flow corridor CWs have been suggested [68].

CWs have few constraints, such as the large area required and the unpleasant odor associated with certain types of treated effluent. CWs demand a prolonged HRT for wastewater treatment, directly affecting the territory's needs [73]. In addition, their effectiveness varies with the season and weather conditions [74]. Despite this, they are viewed as environmentally friendly and sustainable methods that demand reduced energy consumption, lower operational and maintenance expenses, and offer essential ecological advantages like wildlife habitat, groundwater replenishment, flood mitigation, and enhanced visual appeal [75].

Phytoremediation in CWs is based on the ability of certain plants to bioaccumulate, degrade, or convert soil, water, or air pollutants into harmless forms. Thus, choosing plants is one important factor in the phytoremediation process in CWs. Table 2 summarizes the main types of plants used in phytoremediation in CW and their ecological functions.

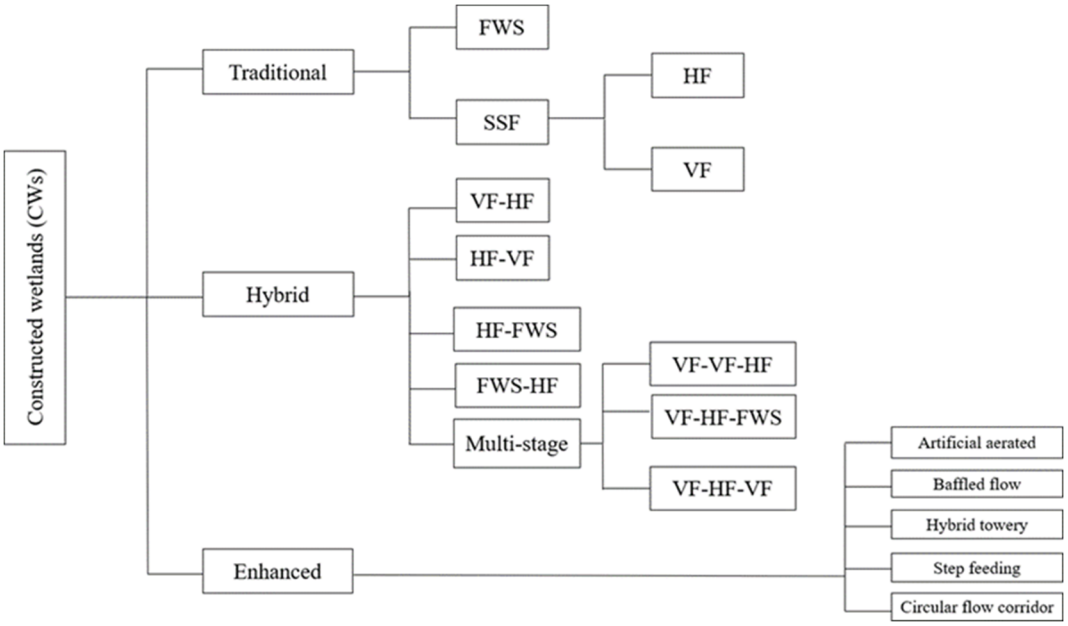


Figure 5. Classification of CWs. FWS: Free Water Surface, SSF: Subsurface Flow, HF: Horizontal Flow, VF: Vertical Flow. Source: [68].

Table 2. Types and effects of plants on phytoremediation in CW.

Plant Type	Effect/Ecological Function	References
Phragmites australis	Growth dynamics, nutrition, and heavy metal shoot accumulation	[64]
Phragmites australis	Metal removal	[76]
Phragmites australis	Biomass growth, removal of Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), pathogens, Total Phosphorus (TP) and Total Nitrogen (TN)	[77]
Typha domingensis	Treatment of wastewater of high pH and EC	[78]
Phragmites australis	Poor Nitrogen absorption capability	[79]
Typha angustifolia	Heavy metal removal	[80]
Typha latifolia	Biomass production, nitrogen absorption and storage	[81]
Typha latifolia	Heavy metal removal	[82]
Typha domingensis	Treatment of mercury-polluted waters	[83]
Eicchornia crassipes	Elimination of nutrients and organic matter	[84]
Trianthema portulacastrum	Removal of Sulfate, Nitrate, Nitrite, Phosphate, TSS and Total Dissolved Solids	[85]
Typha angustifolia	Accumulation of Ibuprofen in foliage cover	[86]
Phragmites australis	Less removal of nutrients and contaminants	[87]
Pistia stratiotes	Phytoextraction potential	[88]
Phragmites australis	Removal of TSS, BOD, COD, TN and TP by 95%, 93%, 91%, 67% and 62%	[89]
Typha domingensis	Phytoextraction and phytostabilization potentials	[90]
Eicchornia crassipes	Remediation of nitrogen-rich wastewater	[91]

Table 2. *Cont.*

Plant Type	Effect/Ecological Function	References
Phragmites australis	Extraction of nonylphenol, diclofenac and atenolol	[92]
Lemna	Removal of nitrates, phosphates and pathogenic bacteria	[93]
Phragmites australis	Removal pf Phenanthrene, Pyrene and Benzo[a]Pyrene by 83%, 71% and 81%	[94]
Pistia stratiotes	Removal of heavy metals from contaminated water	[95]
Pistia stratiotes	Decrease in Cd (27.15%), Pb (42.4%) and EC (65.6%) in industrial sewage sludge	[96]
Typha latifolia	Elimination of microbial and chemical impurities from water	[97]
C. laevis	Greywater treatment	[98]
Oenanthe javanica, *Mentha aquatica* and *Lysimachia nummularia*	Nitrogen and Phosphorus removal by 52% and 85.2%, respectively	[99]

The most used plants in phytoremediation in CWs are *Phragmites australis*, *Pistia stratiotes*, *Typha domingensis*, and *Typha latifolia*. However, these plants are mainly aquatic and only correspond to CWs. For the GR case, *Typha latifolia* and *Typha domingensis* could potentially survive only if it is designed to mimic wetland conditions with significant water retention. Meanwhile, *Phragmites australis* and *Pistia stratiotes* are less suitable for GRs without specialized water-holding systems. Many studies have been performed in CWs to eliminate contaminants from greywater. Table 3 shows the results with the percentage of reduction and the types of plants used.

Table 3. Papers related to EC and removal of nutrients and heavy metals.

Element Removed	Reduction Percentage (%)	Plants' Type	References
Cr, Ni, Fe	86, 95, 67	*Eicchornia crassipes*, *Typha domingensis*, *Panicum elephantipes*	[100]
N, P	53, 70	*P. arundinacea*	[101]
Cr, Cu, Zn, Pb, Ni and Mn	-	*T. angustata*	[102]
TP, Standard Reduction Potential	50.3–76.9 and 40.1–68.4	*Cyperus flabelliformis* Rottb.	[103]
Ni, Cr, Cu, Co and Zn	76.4, 66.2, 68.3, 54.6, 99.3	*T. angustifolia*	[80]
Na, K	20–60	*Bassia indica*	[104]
Na	-	*Bassia indica*	[105]
Cd, Cu, Pb, Zn	7, 60, 20, 73	*Typha latifolia*, *Phragmites australis*	[106]
Cu, Ni, and Cr	97.1, 94.3, 84.4	*Leersia hexandra*	[107]
Total Kjeldahl Nitrogen (TKN), Cd (II), Hg (II), Cr (VI) and Pb (II)	67, 92–98	*Gynerium sagittatum*, *Colocasia esculenta* and *Heliconia psittacorum*	[108]
NO_3^-, PO_4^{3-}	51.9, 8.9	*Canna*	[109]
Zn (dry and wet season)	70.03, 64.51	*Azolla pinnata*	[110]
Cd, Ni	87.1, 86	*Typha domingensis*	[111]
Cd, Zn, Ni	91, 82–98, 61	*Juncus acutus*	[112]
Cr(VI)	97.2–98.3	*Tradescantia pallida*	[113]

Table 3. *Cont.*

Element Removed	Reduction Percentage (%)	Plants' Type	References
TP	68	*Canna-lily*	[114]
Zn, Cu, Pb, Cd	86, 60, 31, 5	*Phragmites australis*, *Typha latifolia*	[115]
TP	60	25 species	[116]
EC	-	*Salicornia europaea*, *Salsola crassa*, and *Bienertia cycloptera*	[117]
NO_3, Na, K, Mg	82, 20, 80, 29	*Juncus maritimus*, *Typha latifolia*, *Cyperus papyrus*	[118]
TP	40	*Typha* spp., *Zantedeschia aethiopica*	[119]
Pb, Cr, Cd and As	45, 27, 18, 73; 51, 28, 21, 73; 75, 62, 57, 87; 65, 50, 34, 80	*Tagetes patula*, *Aster amellus*, *Portulaca grandiflora* and *Gaillardia grandiflora*	[120]
N-NO_3, P-PO_4	44, 41.7, 40.3; 45.1, 57.2, 55	*Canna indica*, *Cyperus papyrus*, and *Hedychium coronarium*	[121]
Cr, As, Ni, Cd, Pb	85, 38, 83, 90, 97	-	[122]
Fe, Al	92, 96	*Azolla filiculoides*	[123]
TP, TN	76, 25	*Flowers (geraniums)*	[49]
COD, TSS	95, 94	*Phragmites karka* and *Eichhornia crassipes*	[124]
N, P	-	*Eleocharis dulcis*, *Typha orien-talis*, and *Scirpus validus*	[125]
N, P	-	Aquatic	[126]

Different plant species are used depending on the specific elements to remove. For instance, *Canna* species is used primarily for Phosphate removal, achieving 8.9, 41.7 and 68% [109,114,121], whereas *Typha latifolia* and *Phragmites australis* are used for removal of Zn (73 and 86%), Cu (60%), Cd (5 and 7%), and Pb (20 and 31%) [106,115]. In addition, *Typha domingensis* could be helpful in removing Ni with 86 and 95% [100,111].

Treating greywater, already applied in CWs, could be used in GRs and GWs. Nevertheless, this shift in NBS will be accompanied by modifications in terms of design and materials (waterproof membrane, protection, filter, and drainage layers exist in GWs and GRs), classification (different types of GWs and GRs compared to CWs), choice of plants (the ones in CWs could not survive in GWs and GRs), and performance (GWs and GRs will affect the building). Thus, these urban wetlands (GWs and GRs) could be the target for phytoremediation studies, taking into account all the previously mentioned challenges.

3.4.2. Urban Wetlands

Urban wetlands are the systems related to cities and buildings. They play a crucial role in green and blue infrastructure, providing several functions. They include GRs, GWs, and, more recently, wetwalls. However, installing and maintaining operational wetlands in urban areas presents numerous difficulties, including diminished hydrological functions, altered water patterns caused by barriers, pollution from wastewater, and habitat destruction due to changes in land use. On the other hand, these wetlands serve distinctive functions because of their placement in complicated city surroundings. Urban wetlands mitigate heat islands' effects, regulate the temperature [106], and offer recreational, holiday, and tourism spaces that support peaceful urban growth [127]. They also have a cooling impact on the surrounding zones, especially during the warmer months, and attenuate severe winds [128]. They also might eliminate contaminants, lessen urban floods, and enhance the quality of the water [129]. Moreover, they provide nesting sites for wetland breeding species [130].

Due to the effects of climate change followed by water scarcity, more focus is being placed on using alternative sources. Reusing greywater is at the top of these ideas. Moreover, research has relied chiefly on CWs requiring huge areas. Nevertheless, this field of research, specifically the phytoremediation process, is shifting towards greenery such as GWs and GRs (urban wetlands). For instance, *Helichrysum* species were shown to have the capacity to act as efficient phytoremediators, while simultaneously supporting these urban wetlands [131].

Green Walls and Wetwalls

Vertical GWs are ideal for urban environments, as they address the challenge of limited horizontal space [132]. Phytoremediation, particularly by implementing active (ventilated) GWs, is increasingly acknowledged as a promising approach to managing air pollution [133]. Moreover, GWs can reduce elevated suspended particulate matter [134]. Table 4 presents the papers on phytoremediation applied in GWs.

Table 4. Phytoremediation in green walls.

Construction System	Improvement	Studied Parameters	Aim	Result	References
Polyvinyl chloride (PVC) columns	Greywater treatment	Potentially suitable growing media, hydraulic and pollutant removal performance	Designing GWs for greywater treatment, drawing on the principles of other vegetated treatment systems, ensuring they are cost-effective while offering a range of additional benefits	Obtaining superior and more consistent pollutant removal efficiency for Slow media compared to Fast media, achieving average removal rates of approximately 90% for TSS, 50% for TN, 30% for TP, 70% for COD, and 80% for *Escherichia coli* (*E. coli*)	[66]
Hydroponic or substrate-based system	Greywater treatment	Plant types, supporting media, metals removal, pathogens removal, pharmaceutical and micropollutant removal	Determining appropriate plants and planting media that can effectively survive and treat greywater, while achieving standard goals and addressing critical operational factors for successful implementation	Removing organic pollutants (approximately 75%) through use of coarse materials like vermiculite, perlite, and sand while minimizing clogging problems associated with finer porous materials. Additionally, biochar shows potential as a promising option, supporting circular material flows	[25]
Wall cascade constructed wetland system (WCCW)	Greywater treatment	Temperature, pH, EC, dissolved oxygen, turbidity, COD, BOD, anionic surfactants, TKN, NH_4-N, NO_3-N, TP, or-tho-P	Integrating the multi-functional advantages of GWs, such as aesthetic and space efficiency, with the high pollutant removal efficiency and water recycling capabilities of CW systems to treat kitchen greywater	Reducing key water pollutants, such as organic compounds and nutrients by WCCW, highlighting its potential for use in urban settings to support water recycling within green infrastructure and ecological sanitation systems	[135]
Modular Vertical Green System (VGS)	Greywater treatment	COD, TP, or-tho-P, TN_b, NH_4-N, NO_3-N	Presenting a VGS for greywater treatment	Using agricultural leftovers led to 92% COD reduction compared to only 67% with wood chips	[136]
Two modular panels, including nine pots each (P1 set in 2020 for this study and P2 in 2018 used before)	Greywater treatment	TSS, BOD, COD, TN, Methylene Blue Active Substances	Examining the efficacy of an experimental GW and assessing its longevity over time	Achieving satisfactory pollutant removal after two levels in case of P_1; however, P_2 showed more variability and frequent clogged problems, necessitating three levels	[132]

Table 4. *Cont.*

Construction System	Improvement	Studied Parameters	Aim	Result	References
Minigarden system: module of propylene with UV protection	Greywater treatment	COD, TSS	Supplying fresh insights on the usage of GW for greywater treatment, with the goal of reusing water while also playing a part in the Circular Economy	Displaying average removal efficiencies of more than 70% for COD and between 59 and 70% for TSS in the case of the mix of coconut and tiles, compared to 60% and 50% with fiber structures	[137]
Pot-based VGS	Greywater treatment	COD, Total Organic Carbon (TOC), TN_b, NH_4-N and turbidity	Assessing the multifunctionality of a pot-based VGS watered with untreated greywater that can also operate as a greywater treatment structure	Obtaining removal percentages of 81% NH_4-N, 80% COD, 79% turbidity, 74% TOC and 70% TN_b	[138]

All the papers mentioned in Table 4 had the same goal, which is treating greywater. However, each one of them had its own construction system and studied parameters. For instance, removal of COD was 92% in modular VGS, 80% with pot-based VGS, more than 70% in a module of polypropylene with UV protection, and 70% in a PVC column.

Da Cunha et al. (2018) [12] proposed a hybrid flow for the Wetwall, which combines HF and VF, creating diverse redox conditions. The living wall hybrid flow aims to improve pollutant removal from urban wastewater, including greywater and hydroponics, by enhancing anoxic conditions in the HF and aerobic conditions in the VF. Greywater treatment involves biological oxidation to remove BOD_5 in VF and phosphates in HF by precipitation and adsorption. The primary purpose of this paper was to demonstrate the potential of the Wetwall design idea as an innovative wastewater treatment solution on an urban scale. The importance of the Wetwall design concept in climate mitigation lies in its sustainable approach to harmonizing technological advancement with natural ecosystems. This is achieved primarily by emulating natural processes and promoting the reuse of resources such as water, nutrients, materials, and energy [12]. Furthermore, the Wetwall design idea introduces a breakthrough ecotechnology for secondary wastewater treatment at the urban scale, including a modular living wall hybrid flow. This proposal combines two proven nature-based solutions/biomimetic designs: CWs and modular living walls. The selection of plants in living walls is very critical. Many authors employed decorative or agricultural plants in their works [12]. Nevertheless, no criteria for selection were mentioned. The Wetwall design idea prioritizes plant selection based on adaptability, environmental benefits, and societal acceptance. The selection of substrates is also considered vital for effective wastewater treatment. The substrate should be lightweight to lower the structure's overall weight and enable its implementation while supporting plant development. When selecting substrates for CWs, it is vital to consider assertive hydraulic behavior and adsorption capabilities to prevent clogging and improve pollution removal by adsorption.

Green Roofs

In recent years, the possibility of using GRs as biofilters to reuse greywater in the built environment has been considered. Using specific technical approaches, a GR involves putting plants on a building rooftop. It consists of multiple layers arranged sequentially from top to bottom: vegetation, substrate, filter sheet, drainage layer, root-resistant barrier, thermal insulation, waterproof membrane, and roof assembly. Moreover, three kinds exist: extensive (substrate depth less than 15 cm), semi-intensive (substrate depth between 15 and 31 cm), and intensive (substrate depth more than 31 cm) [139]. These roofs have

some disadvantages, including runoff quality, roof leakage, cost, and maintenance [140]. Nevertheless, they provide a range of potential economic and environmental advantages such as reducing peak runoff flow during heavy storm events, buffering rainwater, mitigating the urban heat island effect, lowering the building's energy demands, providing sound insulation and noise reduction, enhancing air quality, increasing the building's aesthetic appeal, protecting the roof membrane, and supporting ecological preservation in urban areas [29,141,142].

The possibility of the phytoremediation process taking place in a GR is not without challenges. Some previous research has addressed this topic. Table 5 presents the papers on phytoremediation applied to GRs.

Table 5. Phytoremediation in green roofs.

Construction System	Improvement	Studied Parameters	Aim	Result	References
Reed bed, Membrane bioreactor (MBR), membrane chemical reactors (MCR), Green roof recycling system (GROW)	Greywater treatment	Climate change/global warming, depletion of abiotic resources, acidification, eutrophication, and human toxicity	Outlining the LCIA for four treatment methods being researched for the recycling of greywater produced by households. Examining the practicality of preparing a substrate mix for large GRs utilizing	Surpassing MBR, MCR and reed beds in the majority of impact assessment categories: GROW	[27]
GR assemblies (50 cm × 50 cm × 25 cm) with the same principle as full-scale vegetated roofs	Runoff quality	Al, Fe, Cr, Cu, Ni, Zn, Cd and Pb	Low-cost aggregates and a biosorbent (Sargassum biomass) to enhance runoff quality	Obtaining high sorption capacity of GR substrates for several metal ions (Al, Fe, Cr, Cu, Ni, Zn, Cd, and Pb). Having GR as pollution sinks for all heavy metal ions. Reducing the acidity of entering water and postponing runoff formation	[143]
Green rooftop of a building	Plant growth and biomass	Water retention capacity	Estimating the plant growth-promoting properties of sodium polyacrylate, a super absorbent polymer, and *Micrococcaceae* HW-2, a plant-growth-promoting bacterium	Adding HW-2 rhizosphere bacteria and sodium polyacrylate to *A. donax*, a drought-resistant plant, significantly increased shoot growth and biomass. Combination of the sodium-type polymer and HW-2 rhizobacterium is effective for successful rooftop greening	[144]
Pot growth experiment	Runoff quality	Al, Cd, Cr, Cu, Fe, Ni, Pb and Zn	Examining *Portulaca grandiflora's* ability to remove metals from polluted GR substrates	Collecting metals (Al, Cd, Cr, Cu, Fe, Ni, Pb, and Zn) from a polluted GR substrate via *P. grandiflora*. Reducing metal concentrations in GRs and enhancing runoff water quality by phytoextraction	[145]
Intensive GR	Greywater treatment	Pollutants	Reusing water resources at a condominium with 40 dwelling units in Lecce, southern Italy	Employing aromatic and medicinal plant species for phytoremediation	[65]

Table 5. *Cont.*

Construction System	Improvement	Studied Parameters	Aim	Result	References
GR	Runoff quality	Substrate and sorption capacity	Examining the water quality from vegetative roofs and providing recommendations for improving runoff quality	Considering substrate sorption capacity and plant phytoremediation potential to enhance water runoff quality. Various sorbents may be added to the vegetative roof substrate, and plant species can remove pollutants from it	[29]
GR	Runoff quality	TSS, TN, TP, heavy metals	Evaluating the application of NBS such as GRs for reducing water and air pollution	Regulating roof runoff volume and peak flows, but possible leaching of pollutants (N and P) from the substrate medium raises environmental concerns.	[146]
A rooftop platform of Konkuk University Complex Practice Building in Chungju, South Korea	Runoff quality	Cu, Zn, Mn, and Cd	Assessing the impact of an unfertilized GR's substrate depth and vegetation on runoff reduction and airborne pollutant purification dependent on rainfall intensity	Increasing substrate depth resulted in a substantial reduction in runoff ($p < 0.05$). Vegetated plots had considerably reduced concentrations of heavy metals (Cu, Zn, Mn, and Cd) in their runoff compared to un-vegetated plots and controls ($p < 0.05$)	[147]

In view of the studies reviewed, it can be seen that one of the main debates has been whether GRs were a source or sink of pollution, rather than the study of the phytoremediation process implementation for the cleaning of greywater. In fact, only two papers focused on phytoremediation and greywater treatment. The first one showed the priority of GRs on MBR, MCR and reed beds in terms of impact assessment categories, while the second one involved the use of aromatic and medicinal plant species for phytoremediation. Furthermore, runoff quality from GRs and phytoremediation are linked and should be considered together in future research.

4. Conclusions

Climate change and its effects on the human environment are increasing. For instance, water scarcity is a vital problem that many countries suffer from, even in Europe. Thus, researchers recently focused on alternative sources such as reusing greywater. Most of their work was performed in CWs, artificial ecosystems in which plants and sometimes substrates generate the phytoremediation process through which pollutants can be removed. The phytoremediation process is substantial and beneficial. It consists of seven different mechanisms: rhizofiltration and rhizodegradation in the rhizosphere, phytostabilization, phytovolatilization, phytoextraction, phytodegradation, and phytodesalination in the aboveground. These mechanisms could be significant in treating water and even the substrate. Moreover, several critical parameters must be considered when dealing with phytoremediation, like soil/substrate characteristics, plant type, hydraulic loading rate, greywater composition, economic factors, and environmental conditions. A combination of greywater treatment through phytoremediation with urban greenery would help close the water cycle as well as make cities more sustainable. This review highlights the importance of the phytoremediation process with its strategies on CWs generally and, more recently, on GWs, wetwalls, and GRs.

Phytoremediation in building-integrated greenery systems is gaining interest, with 30% of prior research focusing on its application. In fact, phytoextraction, phytostabilization, rhizodegradation and rhizofiltration already occur in GRs. Thus, a shift in research towards urban wetlands could be explored. These types of roofs and walls provide the same benefits as the CWs but also provide multiple other ecosystem services to the built environment, such as energy and acoustic insulation, building materials protection, Urban Heat Island reduction, run-off control, support to biodiversity, among others. Therefore, phytoremediation in urban wetlands could be an option to enhance the previously mentioned benefits. However, this change in the field from CWs to urban ones is accompanied by several challenges, such as the area available on the roof/wall compared to the enormous area used in CWs, the exact volume of water needed in light of the water scarcity situation, and the choice of substrate and plants which are essential for the phytoremediation.

The reviewed articles mention, but do not address, the possible challenges related to the social and cultural acceptance of these natural greywater purification systems in urban environments in which citizens have lost contact with the dynamics of natural processes, which are often "dirtier" and tend to give off certain odors to which they are no longer accustomed.

Hence, future research on phytoremediation in GWs, wetwalls, and GRs is needed. As mentioned in the results of this review, a vast potential exists in shifting phytoremediation from CWs to urban ones despite some challenges that must be overcome. Consequently, these new studies could be a way to improve the overall performance of these innovative roofs or walls and contribute to the circular economy.

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Abbreviations

The following abbreviations are used in this manuscript:

BIG	Building-Integrated Greenery
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CW	Constructed Wetland
DO	Dissolved Oxygen
EC	Electrical Conductivity
ED	Ecomimetic Design
FWS	Free Water Surface
GR	Green Roof
GROW	Green Roof Recycling System
HF	Horizontal Flow
HLR	Hydraulic Loading Rate
HRT	Hydraulic Retention Time
LCIA	Life Cycle Impact Assessment
MBR	Membrane bioreactor
MCR	Membrane Chemical Reactor
MP	Microplastics
NBS	Nature-Based Solutions
PVC	Polyvinyl Chloride
SSF	Subsurface Flow
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorous
TSS	Total Suspended Solids
UV	Ultra Violet
VGS	Vertical Green System
VF	Vertical Flow
WCCW	Wall Cascade Constructed Wetland
Symbols	
Al	Aluminum
As	Arsenic
Cd	Cadmium
Co	Cobalt
Cr	Chromium
Cu	Copper
Fe	Iron
Hg	Mercury
Mg	Magnesium
Mn	Manganese
N	Nitrogen
Na	Sodium
Ni	Nickel
NO_3^-	Nitrate
Pb	Lead
PO_4^{3-}	Phosphate
Se	Selenium
U	Uranium
Zn	Zinc

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