CZECH UNIVERSITY OF LIFE SCIENCES – PRAGUE

Faculty of Environmental Sciences

BACHELOR THESIS

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CZECH UNIVERSITY OF LIFE SCIENCES, PRAGUE

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BACHELOR THESIS

Filter Media and its uses in Green Walls for treating Greywater

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CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Environmental Sciences

BACHELOR THESIS ASSIGNMENT

Joel Alexander Moses

Environmental Engineering

Thesis title

Filtrační média a jejich použití v zelených stěnách pro úpravu šedé vody

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Objectives of thesis

The objective of this thesis is to investigate the effectiveness of filter media in green walls for treating greywater and to assess the potential of this technology for sustainable water management in urban areas. The specific objectives are: To review the literature on filter media types and their characteristics for greywater treatment in green walls. To evaluate the performance of different filter media in green walls for greywater treatment in terms of physical, chemical, and biological parameters. To analyze the cost-effectiveness of using green walls with filter media for treating greywater. To provide recommendations and guidelines for the design, installation, and maintenance of green walls with filter media for greywater treatment.

Methodology

The methodology of this research paper will explore the opportunities of the reuse of greywater using green walls. A basic overview on greywater and some conventional treatments used and green walls which includes: the types of green wall designs and distinguishing its efficiency in treating greywater. Special emphasis will be placed on the filter media on the functional performance of the green wall and for the growth of plants and its suitability. The aim of this work is a comprehensive description and arrangement of available obtained information from sources (i.e., available literature and scientific articles), which are related to the topic of the work of green walls, especially related to its treatment of greywater. The work will be compiled and evaluated information in the form of a literary research. The literature part of this thesis will be focused on the technical parameters of green walls, the chemical characteristics of greywater, green wall design and its construction with technical parameters and basic overview for filter media and plants in green walls. The practical part of this thesis will be focused on summarizing the performance of different type of filter media used in green walls for the treatment of greywater and its efficiency for the removal of pollutants.

The proposed extent of the thesis

40 pages

Keywords

grey water, green walls, graywater, filter, plants

Recommended information sources

Boano, F. et al. (2021) “Evaluation of the influence of filter medium composition on treatment performances in an open-air green wall fed with Greywater,” Journal of Environmental Management, 300, p. 113646.

Chua, G.X. et al. (2020) “Lake water treatment using green wall system: Effects of filter media ratio and lake water flow rate on treatment performance,” Water Conservation Science and Engineering, 5(3-4), pp. 147–158.

Rysulova, M., Kaposztasova, D. and Vranayova, Z. (2017) “Green Walls as an Approach in Grey Water Treatment,” IOP Conference Series: Materials Science and Engineering, 245, p. 072049.

Shaikh, I.N. and Ahammed, M.M. (2022) “Quantity and quality characteristics of greywater from an Indian household,” Environmental Monitoring and Assessment, 194(3).

Thomaidi, V. et al. (2022) “Use of green roofs for greywater treatment: Role of substrate, depth, plants, and recirculation,” Science of The Total Environment, 807, p. 151004.

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The Bachelor Thesis Supervisor

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Prague on 29. 03. 2023

BACHELOR THESIS AUTHOR'S DECLARATION

I hereby declare that I have independently elaborated the bachelor/final thesis with the topic of: Filter Media and its uses in Green Walls for treating Greywater and that I have cited all of the information sources that I used in the thesis as listed at the end of the thesis in the list of used information sources. I am aware that my bachelor/final thesis is subject to Act No. 121/2000 Coll., on copyright, on rights related to copyright and on amendments of certain acts, as amended by later regulations, particularly the provisions of Section 35(3) of the act on the use of the thesis. I am aware that by submitting the bachelor/final thesis I agree with its publication under Act No. 111/1998 Coll., on universities and on the change and amendments of certain acts, as amended, regardless of the result of its defence. With my own signature, I also declare that the electronic version is identical to the printed version and the data stated in the thesis has been processed in relation to the GDPR.

29.03.2022 Joel Alexander Moses

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Thank you.

Abstract

This bachelor thesis is focused on the use and functions of green walls for the treatment of greywater, concerning filter media and the choice of materials according to their efficiency for removing pollutants in greywater. The necessary information was obtained from professional articles and journals. The work also describes greywater characteristics, standards, regulations, introduction to green walls and their designs, and the role of plants and filter media in green walls. The work also has technical data on filter media in green walls and a description of the materials.

Keywords: grey water, green walls, graywater, filter, plants

Abstraktní

Tato bakalářská práce je zaměřena na využití a funkce zelených stěn pro úpravu šedých vod, týkající se filtračních médií a výběru materiálů podle jejich účinnosti pro odstraňování škodlivin v šedých vodách. Potřebné informace byly získány z odborných článků a časopisů. Práce také popisuje charakteristiky šedé vody, normy, předpisy, úvod do zelených stěn a jejich návrhy a roli rostlin a filtračních médií v zelených stěnách. V práci jsou také technické údaje o filtračních médiích v zelených stěnách a popis materiálů.

Klíčová slova: šedá voda, zelené stěny, šedá voda, filtr, rostliny

Table of content

Introduction

Filter media refers to a substance or material that is used to remove impurities, contaminants, or pollutants from a fluid or gas. By removing harmful pollutants and enabling the reuse of this water for irrigation, filter media is essential to the treatment of greywater in the setting of green walls. Greywater is the term used to describe wastewater produced by appliances like sinks, showers, and laundry machines. If not properly treated, this kind of wastewater may contain dangerous pollutants and contaminants that damage the environment. Greywater can be treated effectively with green walls by removing pollutants and impurities with the help of plants and filter material. Placing a layer of porous substance, such as gravel or sand, at the base of the wall to serve as a filter is how to filter media used in green walls. Before being used to irrigate plants inside the green wall, greywater goes through the filter media, which removes impurities and pollutants. There are many advantages to using filter media in green walls to clean greywater. By enabling the utilization of greywater and lowering the need for freshwater, it first aids in water conservation. The number of contaminants and pollutants released into the environment is decreased, which hurts the ecosystem. One of the most crucial aspects of greywater in green walls depends on the filter material used. Its use is a sustainable and environmentally beneficial method of water conservation and environmental protection.

Objectives

The objective of this thesis is to investigate the effectiveness of filter media in green walls for treating greywater and to assess the potential of this technology for sustainable water management in urban areas. The specific objectives are: 1) To review the literature on filter media types and their characteristics for greywater treatment in green walls. 2) To evaluate the performance of different filter media in green walls for greywater treatment in terms of physical, chemical, and biological parameters. 3) To analyze the cost-effectiveness of using green walls with filter media for treating greywater. 4) To provide recommendations and guidelines for the design, installation, and maintenance of green walls with filter media for greywater treatment.

Literature Review

3.1 Greywater

3.1.1 Characteristics

Grey water, which can also be spelled as grey water, refers to water that has already been utilized in residential, commercial, or industrial settings. This encompasses the untreated water that remains after activities such as using washing machines, taking baths, and washing hands in bathroom sinks (Foundation, 1977).

Greywater is a type of household wastewater that comes from various sources such as sinks, bathrooms, kitchens, and laundries. It accounts for 50-80% of the total water usage in a typical household and is considered a dependable source of water. Greywater can be divided into two categories based on the level of contamination: dark greywater (DGW) and light greywater (LGW). LGW contains a mixture of substances like soaps, skin cells, hair, toothpaste, shampoos, lint, body fats, sand/clay particles, and small traces of urine and feces. On the other hand, DGW consists of materials such as dishwashing detergents, raw meat washing, tea, coffee, dairy products, food and vegetable residue, sand and clay particles, fruit and vegetable peels, oil and fats, paints, perfumes, bleaches, non-biodegradable fibers from clothing, solvents, and chemicals from detergents (Shaikh & Ahammed, 2022).

Table 1. Greywater Source and their characteristics. Source: (Samir Mahmoud et al., 2021).

Greywater Source	Constituents
Kitchen	Kitchen greywater is composed of leftover food particles, large amounts of oil and fat, and detergents used for dishwashing. It may sometimes include substances like drain cleaners and bleach. This type of wastewater is rich in nutrients and suspended particles. Dishwasher greywater, which is also part of kitchen wastewater, can have a high alkaline level due to the presence of detergent builders. It also contains high levels of suspended solids and salt concentrations.
Bathroom	Among the different sources of greywater in a household, bathroom greywater is generally considered to be the least polluted. It typically consists of wastewater from activities such as washing hands, brushing teeth, and using body care products like soap, shampoo, and toothpaste. In addition, bathroom greywater may contain materials like shaving waste, skin, hair, body fats, lint, and small amounts of urine and feces. Greywater from showers and baths can be particularly concerning as it may contain harmful microorganisms.
Laundry	Greywater generated from laundry activities contains elevated levels of various chemicals present in laundry detergents, such as sodium, phosphorus, surfactants, and nitrogen. In addition, laundry greywater may contain bleaches, suspended particles, and potentially harmful materials like oil paints, solvents, and non-biodegradable fibers that are present in clothing. There is also a risk of laundry greywater being contaminated with pathogenic microorganisms, particularly when washing items like diapers.

Greywater has a temperature range between 18 and 35°C and this high temperature could be caused by activities like cooking and personal hygiene (Oteng-Peprah et al., 2018).

Common contaminants found in greywater are salts, food particles, oil, surfactants, and microorganisms (Murthy et al., 2016). Table 2 below shows the average characteristics of greywater generated from a normal middle-class household.

Table 2. Average characteristics of greywater generated from a normal middle-class household in India (Murthy et al., 2016).

Parameters	Bath/Shower	Washbasin	Kitchen	Laundry	Average
pH	7.5	7.5	6.2	9.4	7.6
TDS (mg/l)	277	237	245	1060	455
COD (mg/l)	461	225	602	824	528
BOD (mg/l)	81	43	293	269	172
TSS (mg/l)	148	48	308	1852	589
Ammonia-nitrogen	2.1	1.6	4.7	10.7	4.8
Nitrate-nitrogen	2.6	2.5	11.4	79	24
Orthophosphorous (mg/l)	0.0	0.0	5.3	18.0	11.7
Fecal Coliforms (MPN/100ml)	930	39	230	430	407

Greywater also includes bacteria, protozoa, and other microorganisms that have been linked to the entry of pathogenic bacteria like *Salmonella and Campylobacter* into greywater. These pathogenic bacteria can spread through bodily contact and improper food handling in kitchens. Poor personal hygiene and the disposal of greywater are the primary contributors to fecal contamination, which is frequent in untreated greywater. According to research (O'Toole et al. 2012), enteric viruses, enterovirus, and *Escherichia coli (E. Coli)* were present in 18%, 7%, and 11% of the samples, respectively. (Oteng-Peprah et al., 2018).

Table 3. Recent standard parameters of greywater.

Standard parameters	Unit	Reference			
		(Subramanian et al., 2020), 2020	(Samir Mahmoud et al., 2021), 2021	(Shaikh & Ahammed, 2022), 2022	(Gawlik, 2017), EU regulation
pH			6.3-7.1		
Turbidity	NTU	112-196	85		≤5
Conductivity	µS/cm		664-1046		
Oil and Grease	mg/l		7		
BOD	mg/l	272-344	37-69	19.9	≤10
COD	mg/l	387-643	101-143	34	
BOD/COD		0.53	0.36-0.48		
TSS	mg/l	223-351			≤10
TDS	mg/l				
TN	mg/l		11-22		
TKN	mg/l		9.5-14.3		
NH4-N	mg/l		4.1-9.1	30	
NO3-N	mg/l		0-1.8		
PO4-P	mg/l		0.45-1.5	130	
BOD/NH4-N/PO4-P			0.6-1.4		
Na	mg/l		32-35		
Cl	mg/l		53		
FC	CFU	2.35×10^8	$(1.2\text{-}3.6)10^3$	3.48×10^2	

These greywater characteristics were taken from multiple studies from the years 2020, 2021, and 2022 to compare them with the EU regulation for minimum standard quality requirements for water reuse in agricultural irrigation and aquifer recharge. In the year 2021, the study was taken by Samir Mahmoud et al, and for most of the parameters, it didn't show any noticeable variations except for a few parameters (BOD, COD, TSS, TDS). In BOD parameters different studies showed different variations for BOD concentrations. A study conducted by Burnat and Mahmoud (2005) showed a concentration of 590 mg/l when compared to study which shows a BOD concentration of 37-69 mg/l, which is a large difference, and it may have been caused by the source of the greywater and country. Different countries and sources have different greywater characteristics. COD concentration varying concentrations according to different studies. According to a study by Gross et al., (2007) 700-980, mg/l is a big difference when compared to the COD concentration by Scheumann et al., (2007) which is 101-143 mg/l. Another parameter that also has a varying degree of concentration would be TSS and TDS. A study by Gross et al., (2007) showed concentrations of 85-286 mg/l and 102 mg/l respectively, while Nolde (1999) showed concentrations of 1389 mg/l and 573 mg/l respectively. All these greywater characteristics when compared to the EU regulation for minimum standard quality requirements for water reuse in agricultural irrigation and aquifer recharge is not up to their standards and studies from the year 2020 and 2022 also vary too because of different countries and source (Samir Mahmoud et al., 2021).

The presence of pharmaceuticals in the environment has caused harmful effects on various species such as vultures, fish, frogs, and duckweed. This has raised significant concerns regarding the risks of drinking water contamination and antimicrobial resistance. The discharge of urban wastewater is typically considered the main contributor of pharmaceuticals in water bodies. However, discharge from hospitals, manufacturing, animal husbandry, and aquaculture can also be significant sources of pharmaceutical contamination in local areas (Wöhler et al., 2020).

Table 4. Micropollutants in Greywater.

Micropollutants	Category	Concentration	Unit	Reference
Amoxicillin	Pharmaceutical	654	m^3 kg^{1}	(Wöhler et al., 2020)
Doxycycline		114		
Oxytetracycline		0.68		
Sulfamethazine		0.16		
Tetracycline		15		
Triclosan	Personal care product	9898	ng/l	(Najmi et al., 2020)
Methylparaben		11400		
Propylparaben		3880		
Deltamethrin	Pesticides	0.012	m^3/ton	(Ariyani et al., 2022)
Permethrin		0.001		
Thiamethoxam		0.043		

For pharmaceuticals, table 4 above demonstrates the dominating pharmaceutical greywater footprint related to veterinary pharmaceutical use. The largest GWF (greywater footprint) resulting from livestock is amoxicillin. The study that was conducted in Germany showed that 53% of amoxicillin was produced, which equaled to 654 m3 kg^{1} (Wöhler et al., 2020). Out of the nine chosen PCPs, triclosan, methylparaben, and propylparaben had relatively high concentrations at the inlet stream, with levels of 9898 ng/l, 11400 ng/l, and 3880 ng/l, respectively. The results make it evident that these components are the most prevalent PCPs in greywater with a high concentration of PCPs (Najmi et al., 2020).

Table 5. Microorganisms found in Greywater.

Microorganism	Concentration (counts/100 mL)	Reference
E. coli	Up to 6.5×10^6	(Samir Mahmoud et al., 2021)
Pseudomonas aeruginosa	Up to 1.4×10^4	
Staphylococcus aureus	From 1.2×10^2 to 1.8×10^3	
Salmonella typhi	Up to 5.4×10^3	
Salmonella spp.	Up to 3.1×10^3	

If greywater is stored in warm temperatures for more than 24 hours and left stagnant, it creates a breeding ground for opportunistic pathogens like *Pseudomonas aeruginosa* and *Aeromonas spp*., as well as biofilm growth from *Legionella spp*. and *Mycobacterium avium*. Additionally, some pathogens, including *E. coli* (which serves as an indicator of coliform organisms) and other coliforms, can survive for extended periods under unfavorable conditions. To link with different infection risks, it's necessary to categorize the microorganisms found in greywater effluent into three distinct areas. Coliforms are usually an indication of bacterial contamination resulting from the fecal-oral transmission, and this may involve *Campylobacter jejuni, Shigella spp., Salmonella spp.*, and *E. coli*. Standard removal and disinfection methods may not effectively eliminate protozoa and viruses, and thus, these microorganisms require identification through indicator species within their classifications (Samir Mahmoud et al., 2021).

Bacteria aren't the only organisms that can be found in greywater, viruses are also abundant and some of them include Enteric viruses like norovirus, hepatitis A or E, rotavirus, and enteroviruses such as poliovirus and echovirus, are common viral species that require caution. Protozoan pathogens that can be transmitted through water include *Cyclospora cayetanensis*, *Giardia lamblia*, and *Cryptosporidium parvum*, with the latter being a useful indicator species because it has high resistance to chlorine. Table 5 above shows the dominating microorganisms in greywater, with *E. coli* showing the highest concentration in grey water according to Samir Mahmoud et al (Samir Mahmoud et al., 2021).

3.1.2 Treatment Methods

- **Conventional Treatment**

The technologies applied for the treatment of greywater include physical, chemical, and biological processes (Oteng-Peprah et al., 2018).

Physical and chemical methods of treatment, such as filtering, adsorption, and reverse osmosis, are included in physiochemical methods of treatment. Examples of biological treatments include activated sludge systems, trickling filters, sewage stabilization ponds, rotating biologic contactors, etc. Biological treatments can use various mixtures of microbes, sunlight, and oxygen. Greywater filtration, rotating biological contactors, membrane bioreactors, and upflow anaerobic sludge blankets have been the most popular and extensively used treatment methods. (Oteng-Peprah et al., 2018).

Filtration is a technique that primarily includes physical treatment and heavily involves the removal of particulate matter. (Oteng-Peprah et al., 2018).

Two different kinds of media screens, also known as large pore filters, micro/nano filtration, and reverse osmosis, are used in the process of filtering. These media can take the form of sand, gravel, fine mesh, and many other things. This treatment has the benefit of being reasonably priced, simple to keep, and effective as a pre-treatment to avoid treatment unit clogging. High efficiency for the pathogen, turbidity, and suspended solids elimination while taking up little room. The drawbacks include its poor ability to remove dissolved organics, which makes it vulnerable to pathogen renewal as well as fouling and clogging. (Maimon & Gross, 2018).

According to research on the use of down flow sand filters, COD, BOD, and TSS had high removal efficiencies, with respective removal efficiencies of 74%, 76%, and 82%. (Abdel-Shafy et al., 2013).

Fixed bed reactors called Rotating Biological Contactors (RBCs) have rotating disks placed on horizontal shafts that are partly submerged as wastewater flows through them. Because the wastewater treatment microbes are open to the air, the dissolved organic pollutants and nutrients can be aerated and taken up by the microbes for degradation. In comparison to other greywater treatment systems, this system has other advantages in terms of operational cost, operational ease, and low technical personnel requirements. It also has advantages in terms of the high removal of organic suspended solids and xenobiotic organic compounds. The drawbacks include a restricted ability to remove pathogens, necessitating subsequent disinfection. (Oteng-Peprah et al., 2018).

The results showed that it can be treated using an RBC system with a reasonably high level of effectiveness. The treatment efficiency of the RBC system based on BOD removal ranged from 93-96% and based on TSS removal it ranged from 84-95%. (Abdel-Kader, 2013).

To cleanse greywater, a membrane bioreactor (MBR) integrates perm-selective and biological processes. For treatment, it combines biological, microfiltration, and ultrafiltration devices. The benefits of this treatment method include its high removal of pathogens, turbidity, and organic suspended solids, as well as its small footprint. In a 2017 research, Atanasova et al. demonstrated how well an MBR treated greywater in a hotel in Spain. Ammonia and total nitrogen had significant levels of removal efficiency, averaging 80.5% and 85.1%, respectively, while COD removal efficiency ranged from 80 to 95 percent. This form of treatment's drawbacks includes a high energy requirement and high capital and operating costs. Professional upkeep is also necessary, and the membrane cleansing process involves using toxic chemicals. (Oteng-Peprah et al., 2018).

One of the most popular wastewater treatment methods is the up-flow anaerobic sludge blanket (UASB), which uses an anaerobic process and maintains a high concentration of active suspended biomass to produce better sludge than other types of treatment systems. The high BOD removal rate, the ability to endure high organic and hydraulic loading rates, and low sludge production are the system's benefits. Its instability under varying hydraulic and organic loads and need for expert operation are its drawbacks. Additional treatment is also required for sludge and effluent, which raises running costs. (SSWM, 2022).

With various hydraulic retention times (HRT) and temperatures, the treatment of greywater in two UASBs was investigated. At 30°C, the entire COD in greywater treated with the UASB reactor was removed with an HRT of 6–16 hours and 52–64% at lower temperatures with an HRT of 8–20 hours. Under any operating circumstances, the removal of total nitrogen and phosphorus was restricted to 22-36% and 10-24%, respectively. (Elmitwalli & Otterpohl, 2011).

- **Nature Based Solution**

Constructed Wetland

Wetlands are natural environments that support a variety of intricate biological and non-biological processes that have the ability to alter substances that are considered harmful pollutants. These pollutants can be removed, broken down or transformed by the wetland's vegetation, microorganisms and soil. Constructed wetlands can be categorized into three main types: horizontal subsurface flow, horizontal free water surface flow, and vertical flow constructed wetlands. Each type has distinct characteristics based on factors such as the presence or absence of free water surface, rooted emergent aquatic plants, and the direction of water flow. The majority of constructed wetlands have plants that are deeply rooted in the soil, but some are free-floating, floating-leafed or submerged (Maiga et al., 2019).

Subsurface configuration constructed wetlands allow water to flow through a medium beneath the surface and can be either horizontal or vertical. In particular, horizontal subsurface flow constructed wetlands have a gravel or sand-filled basin planted with wetland vegetation, and water flows horizontally through the filter media. The filter media aids in the filtration of particles with the help of microorganisms that degrade organics. Conversely, vertical flow constructed wetlands have a planted filter bed at the bottom that drains, and water is distributed onto the surface through a mechanical dosing system. The water flows vertically through the filter media and is drained at the bottom via drainage pipes (Maiga et al., 2019).

Surface flow wetland systems have plants that grow on porous media and the water is visible on the surface, typically at a depth of 0.15 to 0.60 meters. This type of wetland system exposes the water to the surface, theoretically providing oxygen and UV disinfection as well (Maiga et al., 2019).

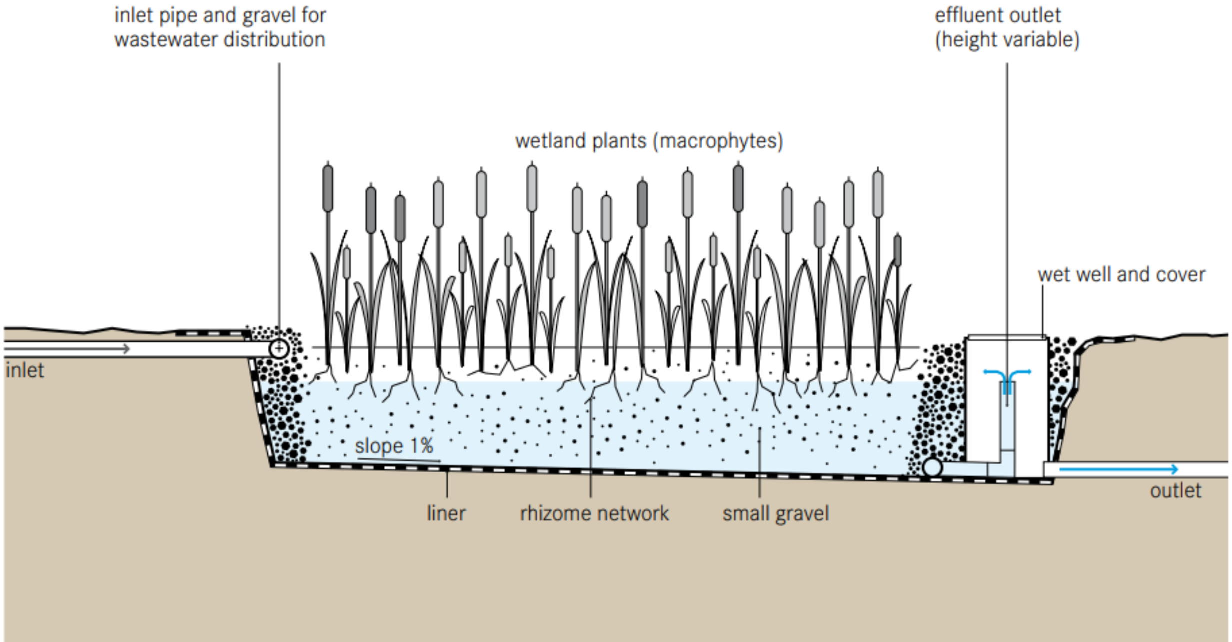

Figure 1. Schematic of Horizontal Sub-Surface Constructed Wetland. Source: (SSWM, 2022).

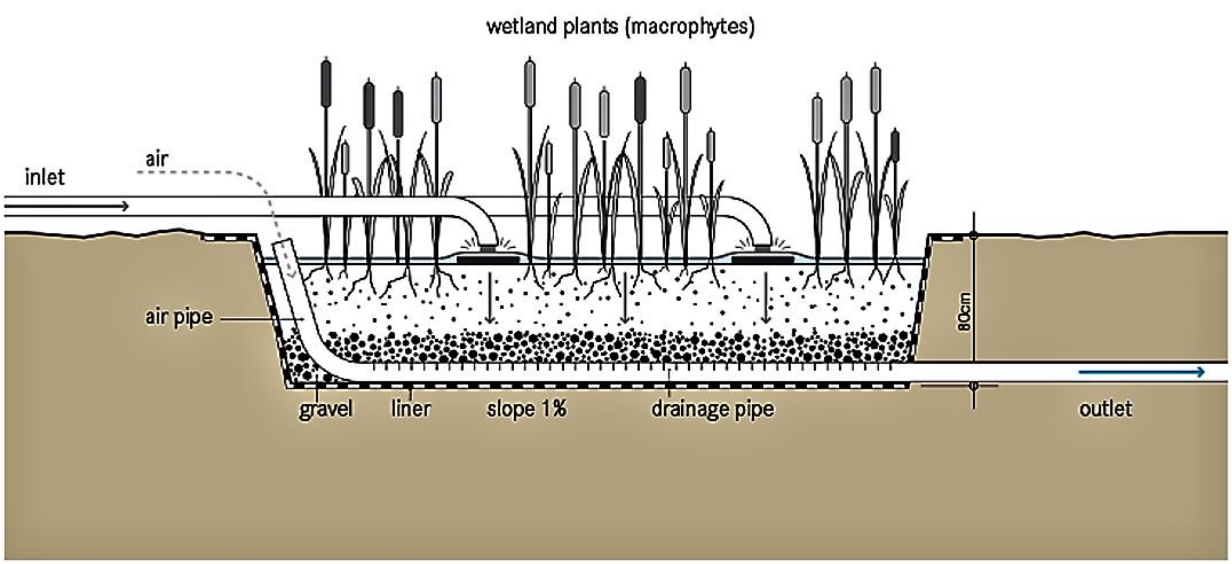

Figure 2. Schematic of a Vertical Flow Constructed Wetland. Source: (SSWM, 2022).

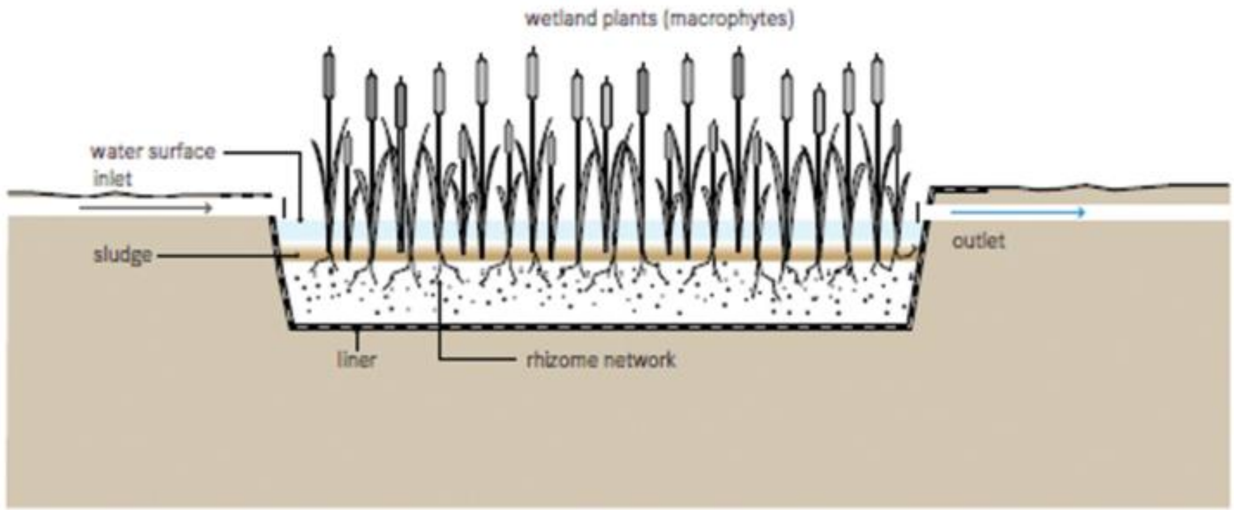

Figure 3. Schematic of a Free Surface Flow Constructed Wetland. Source: (SSWM, 2019).

Green Roof

A green roof is a layer of vegetation that is planted over a waterproofing system and can be installed on a flat or slanted rooftop (National Park Service, 2022).

Green roofs can be categorized into two types extensive and intensive, with the first type having growing media with a depth ranging from 2 to 15 cm, while the second case can have substrate depths of more than 15 cm applied. The growing media are usually light and should be well-draining in general with materials such as compost, coco coir, peat, perlite, vermiculite, zeolite, lightweight expanded clay aggregates (LECA), and lava rocks being some good examples of these. Green roofs have many similarities with constructed wetlands, being an application of one, and can be characterized as a modified subsurface constructed wetland with both systems consisting of substrate and vegetation layer. Green roofs have been shown to have good removal efficiency of suspended solids and turbidity >90%) and moderate to high removal efficiencies of organic matter (60–80% COD removals, 80–97% BOD removals) in greywater. Studies showed that intensive green roofs with 20 cm of vermiculite and 5 cm of LECA were able to treat light greywater efficiently compared to extensive green roofs with shallow growing media (<15 cm). The extensive green roofs achieved lower effluent quality regarding physical (turbidity, total suspended solids) and chemical (organic matter, nitrogen, phosphorus) characteristics (Thomaidi et al., 2022).

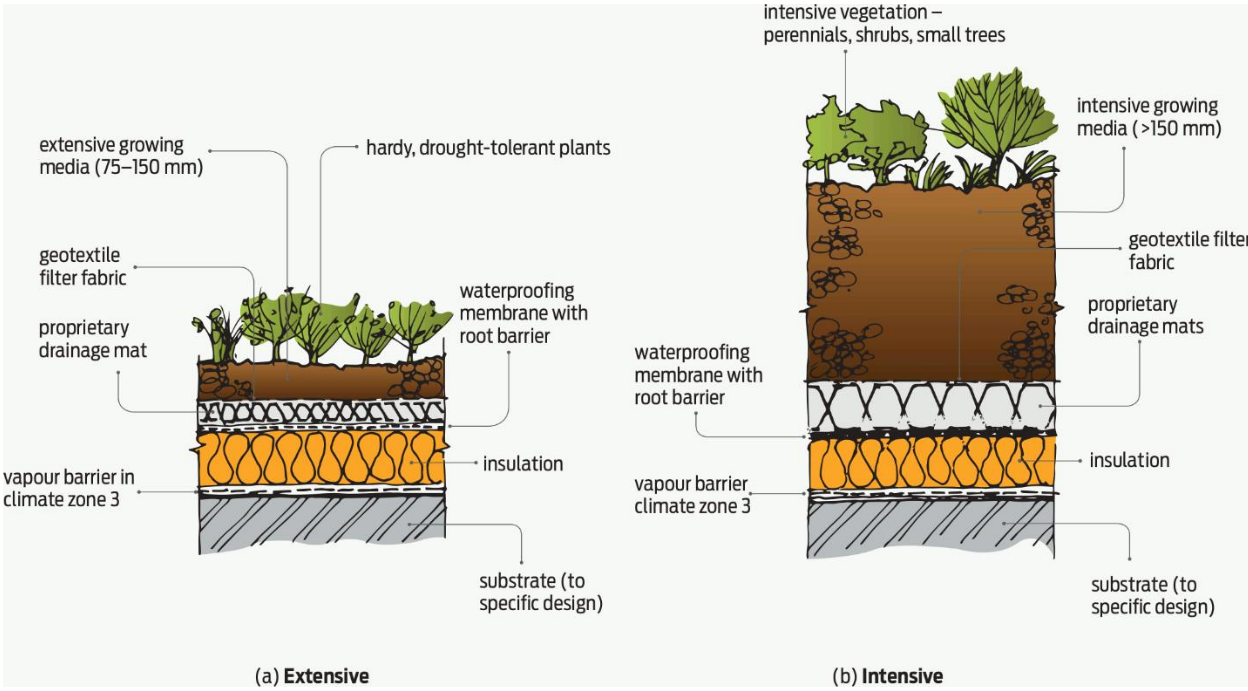

Figure 4. Schematic of Extensive and Intensive Green Roof. Source: (Elkink & Alide Elkink Freelance Technical Writer, 2022).

3.1.3 Greywater Regulation

Greywater is defined as relatively clean wastewater that is produced from household activities like washing dishes, and clothes, and taking showers or baths. The reuse of greywater is an effective way to conserve water resources and reduce the volume of wastewater that must be treated and discharged into the environment. However, there are specific rules and regulations in place to ensure that the reuse of greywater does not pose any danger to human health or the environment. The European Union has established various directives and regulations to govern the reuse of greywater. For example, the Urban Waste Water Treatment Directive (91/271/EEC) sets minimum standards for the collection, treatment, and discharge of urban wastewater. The Water Framework Directive (2000/60/EC) establishes a framework for protecting and managing water resources in the EU, and the EU Regulation on Water Reuse (2018/841) establishes minimum requirements for the reuse of treated wastewater for agricultural irrigation, urban landscape irrigation, and groundwater recharge. This regulation also includes specific provisions for the treatment of greywater for reuse purposes. In addition to these EU directives and regulations, individual member states may have their national standards and regulations for greywater reuse.

The main legislative framework for water protection in the European Union (EU) is the Water Framework Directive (WFD) established by the Council Directive 2000/60/EC of the European Parliament. The primary objective of the WFD is to maintain and enhance the quality of aquatic environments by setting environmental goals for surface water, groundwater, and protected areas. EU member states are obligated to prevent any decline in the status of all water bodies and to reduce or prohibit the entry of pollutants into groundwater by enforcing necessary measures. Another significant EU directive related to water protection is the Urban Waste Water Treatment Directive (UWWTD) established by Council Directive 91/271/EEC. The purpose of this directive is to prevent any detrimental effects on water bodies resulting from the discharge of urban wastewater. In 1998, Directive 98/15/EC was issued to amend Directive 91/271/EEC and establish requirements for discharging to vulnerable areas prone to eutrophication. It is important to note that in the Czech Republic, all surface waters are considered vulnerable areas, so stricter regulations apply to them (Ing David Stránský, 2017).

In the Czech Republic, greywater reuse is governed by several regulations and guidelines, including the following:

Water Act (Act No. 254/2001 Coll.): This law regulates the protection, use, and management of water resources in the Czech Republic, including the reuse of greywater. It requires that all water resources be managed in a sustainable and environmentally sound manner and that all discharges into water bodies meet certain quality standards.

Decree on the Requirements for Wastewater Treatment Plants (Decree No. 61/2003 Coll.): This decree establishes technical and quality requirements for the design, construction, and operation of wastewater treatment plants in the Czech Republic. It includes provisions for the treatment of greywater and other types of wastewaters.

The Water Framework Directive (WFD) and the Urban Waste Water Treatment Directive (UWWTD) have been incorporated into the Water Act 254/2001 Col., as amended, in the Czech Republic. This act establishes conditions for the use of surface water and groundwater, integrates flood protection, defines the obligations of natural and legal persons related to water protection, and sets the definition of wastewater and obligations arising from discharging wastewater into the environment. The Act 274/2001 Col., on public water mains and sewerage, as amended, incorporates UWWTD requirements to regulate the development, construction, and operation of water supply and sewerage systems. Government Regulation No. 401/2015 Col. establishes threshold values for all major pollutants and indicators of pollution for surface waters and wastewater and lays down the requirements for obtaining a license to discharge wastewater. Act No. 185/2001 Col. on waste defines sewage sludge from WWTPs and septic tanks as waste and restricts its use in agriculture. Decree 501/2006 Col. defines stormwater management priorities for building land and establishes infiltration as the preferred way of stormwater management for new houses. If infiltration is not possible, stormwater must be retained on the site and gradually discharged into separate stormwater networks or transported to receiving water bodies. If this is not possible, it is allowed to discharge stormwater into combined sewage networks (Ing David Stránský, 2017).

3.2 Green Walls Introduction

3.2.1 History of Green Walls

The ancient civilizations of Babylon and China utilized the concept of green walls, or living walls and vertical gardens, for both functional and decorative purposes. The Hanging Gardens of Babylon, constructed around 600 BC, featured terraced gardens filled with various plants, while in China, vertical gardens were created on walls of houses and temples as early as 300 BC. These were the first recorded instances of green walls in history.

The modern concept of green walls gained prominence in the mid-20th century, particularly in Europe. The first modern green wall system was developed in the 1930s by Professor Stanley Hart at the University of Illinois, using a trellis system to support plants grown in soil. Patrick Blanc, credited with pioneering the modern green wall system in the 1980s, utilized a hydroponic system to grow plants directly on vertical surfaces. Blanc's first green wall installation was at the Cité des Sciences et de l'Industrie in Paris in 1986, and he went on to create more installations worldwide, including the Musée du Quai Branly in Paris, the CaixaForum in Madrid, and the One Central Park development in Sydney, Australia.

Today, green walls are becoming increasingly popular in urban areas to add greenery to buildings, reduce the heat island effect, provide habitats for birds and insects, reduce noise pollution, and improve air quality. They are also being used for innovative and eco-friendly water treatment and filtration, a concept first coined by Dr. John Todd in the 1970s, who developed the idea of an "eco-machine," a closed-loop system that utilizes plants and microorganisms for wastewater treatment and purification.

Since, the initial work of Dr. Todd, green walls for the treatment of water treatment have been implemented all around the world in different projects. One of the most prominent examples would be the vertical wetland system used in the 2008 Beijing Olympic Village. This system consisted of a 200-meter-long green wall that used plants to filter and treat wastewater from the village and this system was able to treat up to 40,000 liters of wastewater per day (Cui and Zhu 2011). Another example would be the green wall at the Atlantis, The Palm hotel in Dubai, which is the largest one of its kind its wall has 20,000 plants that treat wastewater from the hotel’s laundry and kitchen and can treat up to 7,000 liters of wastewater every day (El-Bery and Gad, 2016). Green walls have also been implemented for smaller-scale projects, such as in residential buildings and public parks. These systems also use plants and microorganisms to filter and treat greywater and blackwater, which are then reused for irrigation or other purposes like non-potable purposes (Langergraber and Pressl, 2014). Several studies have been conducted on the effectivity of green walls for the treatment of water. A study found that a green wall system was able to remove 94% of nitrogen, 78% of phosphorus, and 94% of COD (chemical oxygen demand) from wastewater (Le-Minh et al., 2013). Another study found that green walls were able to remove 99% of total suspended solids (TSS) and remove up to 94% of chemical oxygen demand (COD) from wastewater (El-Bery and Gad, 2016).

Green walls have a long history of use for various purposes which include water treatment. Dr. John Todd's work on green walls laid the foundation of the modern green walls that are being used for the treatment of water and since then they have been implemented in various projects and studies have shown their effectiveness in removing contaminants in wastewater.

3.2.2 Green Wall Benefits

Air Quality

The comprehensive research conducted in 2016 revealed that the World Health Organization identified a connection between inadequate air quality and over 5.5 million early deaths each year (Biotecture, 2021).

Green walls that are alive can function as natural air purifiers and improve the quality of the work environment, promoting the overall health and well-being of the occupants. Toxins such as formaldehyde, carbon monoxide, benzene, and VOCs are frequently encountered by individuals in indoor settings. Living green walls can break down harmful pollutants and release oxygen into the air, like indoor plants but on a larger magnitude (ambius, 2023).

Throughout the day, as a part of photosynthesis, plants remove carbon dioxide, carbon monoxide, and several other pollutants from the air, resulting in a notable decrease in CO2 levels in urban areas that are adequately vegetated (urban greening, 2017).

Noise Level

Living green walls offer an advantage that is not widely acknowledged, which is the ability to lower noise levels in buildings. In residential areas, plants have been utilized as a barrier against noise pollution from nearby highways and roads. Living green walls enhance this approach by using vegetation as a natural blocker of high-frequency sounds. Furthermore, the structure that supports the plants can help to minimize low-frequency noise. The layer of air between the wall and the plants, created by living green walls, serves as additional insulation, while the walls themselves can diminish noise levels by reflecting, refracting, and absorbing acoustic energy (ambius, 2023).

Surfaces that are planted tend to reflect noise at low levels and have a greater ability to absorb it. The use of ivy screens and living hoarding can lessen ambient noise, which can have a positive impact on the people who work or reside in the building as well as pedestrians (urban greening, 2017).

Temperature

The scientific study of climate change anticipates that by 2050, London will encounter temperatures that are comparable to what is presently experienced in Marseilles. The issue is that London, as well as other cities in the UK, were not constructed to withstand these prolonged periods of high temperatures. Furthermore, there are various street-level areas where heat becomes trapped (Biotecture, 2021).

Urban areas tend to have a higher mean temperature than the neighboring rural areas. By increasing vegetation in areas of intense heat in cities, also known as urban canyons, the canopy cooling effect of the vegetation helps to decrease trapped air temperatures and lessen the amount of heat that is reflected (urban greening, 2017).

A living wall is installed on the surface of a building to provide shade and absorb heat, thereby preventing the building surface from absorbing solar radiation and emitting it back into the environment. This can help reduce the amount of energy used by the building. Additionally, the living wall acts as a buffer against extreme temperatures in both summer and winter, making the environment more pleasant (Biotecture, 2021).

According to tests conducted, there have been temperature variations of as much as 17ºC between areas with hard surfaces and those with vegetation in the same location (urban greening, 2017).

Biodiversity

The use of diverse plant species in a green wall can significantly enhance the population and diversity of insects and birds in a specific region, contributing to the restoration of a more sustainable ecosystem in urban settings (urban greening, 2017).

The maintenance team has observed bees collecting nectar from the flowers at the top of the Edgware Road living wall. The purpose of this wall was to reduce air pollution in the area, as the busy main road at its base is one of the major sources of air pollution. However, the bees are not concerned about the reason for the wall's installation. They simply see it as a resource they can use for their benefit. In collaboration with Buglife, the team designed and developed integrated habitat boxes that fit neatly into their living walls. These boxes provide shelter for a variety of species, such as solitary bees, butterflies, ladybirds, and lacewings. For instance, their 1,800m2 living wall on the Veolia Energy from Waste Facility in Leeds contains 750 of these boxes, contributing to a well-balanced local ecosystem. In addition to increasing plant biodiversity, living walls also offer crucial nesting space, shelter, and food for birds and insects. Bees and butterflies are often spotted on their living walls within days of installation. Whenever possible, the team prefers to work with native plants and has developed a reliable and robust list of them over time (Biotecture, 2021).

3.3 Green Wall Designs

Green walls can be classified into two main categories: Green Facades and Living Walls, which can be further divided into subcategories. Green facades are composed of climbing plants that grow directly on a wall or in specially designed structures. The plants' shoot system grows vertically on the building while being rooted to the ground. In contrast, living walls are made up of modular panels consisting of polypropylene plastic containers, geotextiles, irrigation systems, growing media, and plants (Burhan & Karac, 2013).

According to Li et al. (2009), passive vegetated treatment systems may be the most suitable option for recycling light greywater, as plants have a high capacity for absorbing nutrients such as nitrogen and phosphorus (Prodanovic et al., 2019).

Moreover, these systems are cost-effective due to their low energy and maintenance requirements. Green walls have the potential to efficiently manage water. While some green walls are currently irrigated with recycled grey water, using vegetated walls as a treatment technology is a relatively new research area. Vegetated walls have the potential to serve as a wastewater treatment technology, in addition to their visual appeal, by utilizing the space on buildings' walls and facades (Rysulova et al., 2017).

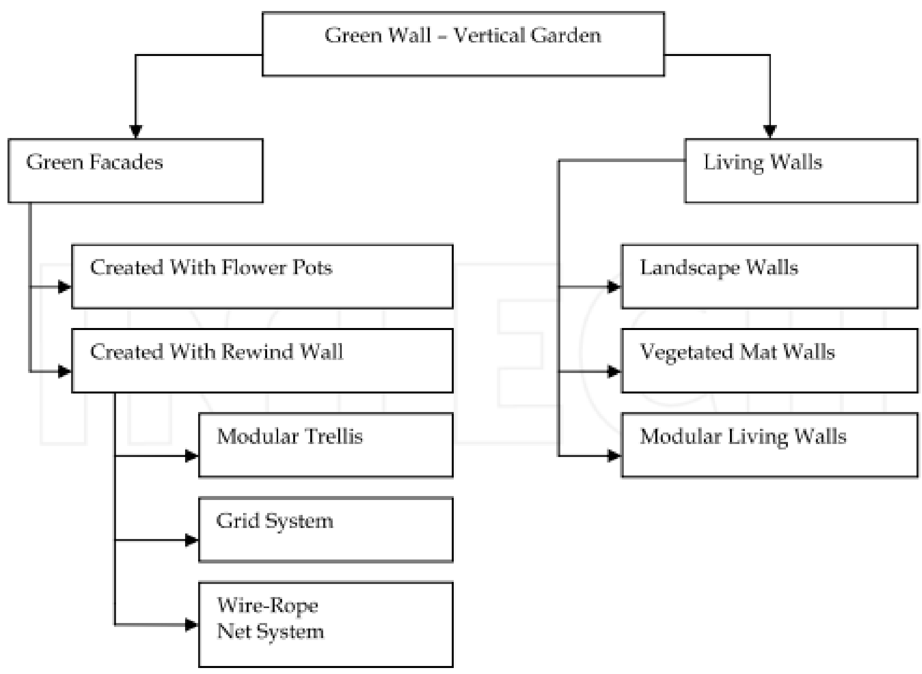

Figure 5. Types of Green Walls. Source: (Burhan & Karac, 2013)

3.3.1 Living Walls

Living walls, also known as vertical gardens or bio-walls, are composed of pre-grown panels, vertical modules, or planted blankets. These panels can be constructed using various materials such as plastic, expanded polystyrene, synthetic fabric, clay, metal, and concrete. Living walls can support a great diversity and density of plant species. Living walls require more maintenance and protection compared to green facades due to their higher density and diversity of vegetation. The living wall system consists of three parts: a metal frame, a PVC layer, and an air layer (instead of soil). This setup allows for a wide range of plant species to be supported, including a mix of vegetation, perennial flowers, low shrubs, ferns, and more (Burhan & Karac, 2013).

Figure 6. Living Wall, Semiahmoo Library in South Surrey. Source: (Burhan & Karac, 2013).

Landscape Walls

These walls are an advanced version of landscape "berms" and are considered an important aspect of "living" architecture. Unlike vertical walls, landscape walls have a sloped design and are primarily used for noise reduction and slope stabilization. These walls are typically made of stacking materials, such as concrete or plastic, with space for growing media and plants (Burhan & Karac, 2013).

Figure 7. Landscape Walls. Source: (Burhan & Karac, 2013)

Vegetated Mat Walls

The "Mur Vegetal" is a distinctive type of green wall developed by Patrick Blanc. It consists of two layers of synthetic fabric with pockets that provide physical support for plants and growing media. A frame supports the fabric walls, and they are backed by a waterproof membrane against the building wall due to their high moisture content. Nutrients are mainly distributed through an irrigation system that cycles water from the top of the system down (Burhan & Karac, 2013).

Figure 8. Vegetated Mat Walls, Madrid Spain. Source: (Burhan & Karac, 2013)

Modular Living Walls

The development of modular living wall systems was influenced by using modules for green roof applications and was aided by several technological advancements. These modular systems typically comprise square or rectangular panels that contain growing media to provide support for plant material (Burhan & Karac, 2013).

Green walls can have a varying design such as vegetated mat walls, vertical gardens with horizontal pots, and more. However, only modular, and container-based designs have been studied for greywater treatment. This is because these designs are lightweight and provide a significant volume of growing media that can be used for removing pollutants. These types of green walls are composed of a vertical framework that supports specially designed containers filled with lightweight filtering materials (such as a mixture of coco coir and perlite) and plants. Container-based green walls are particularly appropriate for greywater treatment because the pots can hold all the pollutants and minimize the risk of cross-contamination, unlike vegetated mat walls that use only a water-saturated felt layer for water distribution. Greywater is expected to be directly introduced into the green wall system at various levels, and the chosen filter media and plants treat it as it flows down by gravity, with the treated effluent being gathered at the bottom for reuse in toilet flushing and irrigation (Prodanovic et al., 2019).

Figure 9. Modular Living Wall Canada (above), Atlanta Botanical Garden (below). Source: (Burhan & Karac, 2013)

Table 5. Removal Efficiency of Modular Living Walls

Country	Removal Efficiency %	Filter Media	Experimental Design	Reference
Italy	BOD_5: 97.7%, COD: 40.4%, TKN: 34.6%, NO_3^-: 25.7%	80% coir, 20% perlite	Modular panels with pots	(Boano et al., 2021a)
Spain	Triclosan: 100%, Methylparaben: 99.5%, Ethylparaben: 100%, Diclofenac: 88.5%, Ibuprofen: 71.9%, acetaminophen: 88.5%	LECA	Vertical stage-wise setup combined with sub-surface horizontal water flow	(Gattringer et al., 2016)

3.3.2 Green Façade

Green facades are a variation of green wall systems that employ climbing or cascading plants. These facades can be attached to pre-existing walls or erected as standalone structures like fences or columns. The Modular Trellis Panel, Grid System, and Wire-Rope Net System are three popular green facade systems used (Burhan & Karac, 2013).

A modular trellis panel system

The modular system is built from a lightweight, sturdy panel that has a three-dimensional shape and is coated with galvanized, welded steel wire. The panel has a grid on its face and depth, and it supports plants. The green facade is held away from the building wall to prevent plant material from attaching to the building. This creates a confined growing environment for the plants, and multiple supports are provided for the tendrils to maintain the building's membrane integrity. The panels can be stacked and combined to cover large areas or shaped to create curves. They are constructed from recycled steel and can be recycled. The panels are inflexible and can span between structures and are used for free-standing green walls (Burhan & Karac, 2013).

Figure 10. Freestanding trellis fence (left), column trellis (bottom), custom trellis shapes (right). Source: (Burhan & Karac, 2013)

Grid and wire-rope net systems

The Grid and Wire-rope net systems, use cables and wires. Grids are utilized for green facades that support climbing plants with denser foliage that grow quickly. Wire-nets, on the other hand, are used to support slower-growing plants that require more support from these systems at closer intervals. Both systems use high-tensile steel cables, anchors, and additional equipment. Flexible vertical and horizontal wire-ropes are connected via cross-clamps to accommodate various sizes and patterns (Burhan & Karac, 2013).

Figure 10. Grid and Wire-Rope Net Systems, MFO Park Switzerland. Source: (Burhan & Karac, 2013)

3.4 Filter Media

Filter medium has been recognized as a crucial component of a green wall for treating greywater, as it manages water flow and eliminates pollutants, in addition to promoting plant health (Boano et al., 2021b).

Researchers have not only studied adsorption as a method of removing contaminants from greywater, but they have also explored a biological mechanism that occurs through the use of filtering media and microbial processes. When greywater passes through the filters, the filter not only strains out solids but also provides a surface for bacteria and microorganisms to attach to. This creates an environment for vegetation to grow, thanks to the constant supply of water, moisture, and nutrients from the greywater. Plants attached to a green wall with roots intertwined in the filter media create an aerobic environment, with oxygen released towards the rooting area. This allows aerobic bacteria to absorb organic matter passing through the filter surface and break it down through biodegradation. The resulting biodegraded nutrients and organic matter are then absorbed by the plants as a source of minerals and nutrients, which creates a fertilization medium for the plants (Satheesh et al., 2021).

The choice of filter media is a critical parameter that affects the treatment efficiency and clogging problems of a green wall, according to studies. In addition, multiple studies emphasized the significance and effectiveness of filter media in eliminating excess nutrients like nitrogen, phosphorus, and metals in a biofiltration system. Nonetheless, certain filter media used in these systems, such as sand and wood particulate, may not be suitable for use in green walls. This is because the vertical structure of the wall requires the filter media to be lightweight to decrease the load on its supporting framework. Currently, biofilters tend to use lightweight materials like perlite, coir, lightweight expanded clay aggregate (LECA), and cork granulate. These materials have established physical properties and water retention capacities that are well-known (Chua et al., 2020).

Research studies have indicated that sand and coconut coir, despite their relatively low permeability, can enhance the contact time between greywater and filter medium, thereby promoting greywater treatment. However, sand's high specific weight can limit its applicability in green walls, while coconut coir is known to degrade over time and release organic carbon. Therefore, a mixture of these filter media with lighter and more permeable materials such as perlite and expanded clay was employed to address these issues and achieve good treatment efficiencies (BOD5: 44-97%, COD: 40-70%, TN: 30-75%, *E. coli*: 60-100%). In another study, eight different filter media (sand, expanded clay, vermiculite, grow stone, Rockwool, fyto-foam, coco coir, and perlite) were compared, and the results indicated that the combination of coco coir and perlite was effective in removing contaminants (with COD removal rates ranging from 55-85%, TN removal rates ranging from 40-80%, and *E. coli* removal rates ranging from 35-90% for perlite: coir ratio below 2:1). This combination also lowered the risk of clogging (Boano et al., 2021b).

Currently, biofilters commonly utilize lightweight materials including perlite, coir, lightweight expanded clay aggregate (LECA), and cork granulate. The physical characteristics and water retention abilities of these media are well-established. In general, cork granulates are effective in removing pollutants due to their high absorption capacity. A group of researchers evaluated the effectiveness of LECA, coir, and perlite in treating greywater. LECA and perlite were found to have similar physical properties and were effective in retaining pollutants, while being infertile to bacteria and pathogens, making them suitable for plant growth. Their high porosity also reduced the clogging effect in the system. According to a study comparing the performance of perlite, LECA, and coir in greywater treatment, coir has the highest removal performance. However, its poor hydraulic performance, which is caused by its high density and susceptibility to physical clogging, hinders its treatment performance. On the other hand, perlite has better overall performance than LECA in terms of total suspended solid (TSS) removal, but its high-water infiltration rate results in low removal performance (Chua et al., 2020).

3.4.1 Inorganic

Perlite

Perlite is a naturally occurring mineral formed from volcanic glass. It is produced when volcanic obsidian glass becomes soaked with water over an extended period, resulting in a distinctive type of volcanic glass. Similar to other volcanic rocks, perlite has a relatively high weight and density in its natural state. It typically consists of the following components: 70-75% silicon dioxide, as well as aluminum oxide, sodium oxide, potassium oxide, iron oxide, magnesium oxide, calcium oxide, and approximately 3-5% water. Chemically speaking, organic compounds are composed of carbon atoms. Since perlite lacks carbon, it is considered an inorganic mineral. The advantage of perlite is that perlite is beneficial for root aeration and has a stable, unreactive structure. It assists in enhancing drainage and is affordable and readily accessible. The disadvantage of perlite is that smaller particles of perlite are prone to wind and air disturbances. Perlite does not hold onto water and lacks nutrients. It tends to float when inundated with excess water (Staff, 2022).

According to the experiment, perlite, a fast filter media, removed 73% of total suspended solids (TSS) from greywater. Regarding perlite as a fast filter media, the spaces between its pores are larger, allowing TSS to pass through the looser arrangement of pores. This means that higher concentrations of TSS can pass through the system without being filtered out. However, as time passes, TSS will gradually begin to fill the void between the pores, resulting in a higher potential for TSS removal. This occurs because as TSS fills the spaces between pores, the pore spaces decrease, causing higher concentrations of TSS to be trapped on the layer of the pores. This leads to a stronger straining effect, removing more TSS from the greywater effluent. The COD removal rate for perlite was found to be 26% (Satheesh et al., 2021).

Throughout the experiment, the TSS removal rate in the Fast columns gradually increased from approximately 30% to 80%. This increase is believed to be caused by the accumulation of sediment within the columns, leading to a reduction in pore space and consequently an increase in the straining performance of the filter media. The Fast media columns exhibited lower and more inconsistent nitrogen removal compared to the Slow columns. Furthermore, drying hurt TN removal efficiency for the Fast media. When subjected to high loading rates followed by three days of drying, perlite experienced nitrogen leaching. Fast media had a TP removal performance of 10-20%, which suggests that retention time plays a significant performance, though it is not certain through which mechanism: microbial activity or mechanical straining. The Fast columns exhibited a slight improvement in performance over time, with average removal rates increasing from 22% to 35%. Drying periods did not have a significant effect on COD removal, and while higher pollutant loading resulted in a slight decrease in treatment performance, the columns rapidly recovered following a return to the regular dosing regime. These results suggest that COD reduction is likely driven by both physicochemical and biological processes due to the significant impact of retention time on removal, pointing to biological activity. An increase in removal over the time of the experiment suggests that natural clogging of the system increases COD straining. The removal of *E. coli* by Fast media types was positive, but it varied. Positive removal was observed only after high loading rates in the Fast columns, indicating that a constant inflow concentration of *E. coli* is necessary to achieve stable removal rates. It is suggested that the initial

E. coli removal is due to adsorption on media, but once the system developed a mature biofilm, biological processes take over, such as adsorption to biofilm, uptake, and biodegradation. The biofilm may also provide effective *E. coli* inactivation through various competition and predation processes occurring on its surface. In summary, perlite is the best fast media type as they were found to have the best hydraulic and treatment performance (Prodanovic et al., 2017).

Figure 11. Perlite Substrate/Filter Media. Source: (Proline, 2021).

LECA

LECA, which stands for lightweight aggregates, is a collection of low-density materials that have various applications in civil engineering and construction purposes. This group of materials is heterogeneous in nature and has been studied extensively by researchers. In recent years, LECA has been increasingly utilized in stormwater management schemes and urban green infrastructure, including applications such as green roofs and walls, permeable pavements, and thermal insulation concretes. This trend has been documented by researchers. The initial use of LECA as a substrate for CW was documented in the early 1990s by Jenssen et al. (1991). LECA is an aggregate material that is both strong and lightweight, with a sintered ceramic matrix that is resistant to water and a nearly spherical shape. Its water absorption capacity ranges from 5% to 25%, and its cation exchange capacity is estimated at 9.5 $cmol \cdot kg^{-1}$. Traditionally, raw materials for LECA production have been clay minerals such as montmorillonite or illite. The composition of LECA is primarily made up of 5-6 major constituents, with 60-70% being SiO_2, 15-18% being Al_2O_3, 4-7% being Fe_2O_3, and 1-4% consisting of MgO, CaO, Na_2O, with other constituents making up less than 1%. (Mlih et al., 2020)

LECA (light expanded clay aggregate) pebbles are created from clay by using specialized rotary kilns that reach temperatures of up to 1200°C. As the clay expands and rotates, thousands of minute air pockets are generated inside the clay, forming round or oval LECA pebbles. The name "light expanded clay aggregate" stems from its exceedingly low weight in comparison to its size, which is due to the presence of gas pockets within the clay. LECA is utilized as a concrete aggregate and is also beneficial as a water filtration medium. LECA, which stands for light expanded clay aggregate, is an ideal sand replacement for filtration due to its exceptional features. Made from clay, LECA is incredibly durable and does not require regular sand replacement. It is easy to backwash, making it an ideal sand replacement in facilities that require frequent cleaning. LECA has a high surface area and can filter both physical and biological contaminants, simplifying the filtration process. LECA's porous structure ensures excellent drainage while still maintaining its filtration properties, making it a superior sand replacement, especially for high-volume applications where traditional sand beds may take a long time to filter water (Banker, 2021).

The disadvantage of LECA clay pebbles has a low water holding capacity (WHC), which means they are not very effective at retaining moisture in a substrate after it has been drained (Storey et al., 2022).

The expanded clay consistently showed a slightly lower TSS removal rate compared to other media due to its larger average fraction size and the washout of fine clay particles (Prodanovic et al., 2017).

In LECA-based constructed wetlands (CWs), particularly in unplanted CWs, adsorption is a major method for removing a wide range of water pollutants. A study showed ammonium adsorption to LECA and found that the maximum monolayer adsorption capacity of LECA was 0.255 mg ammonium per gram. The highest adsorption capacity occurred between pH 6-7, and equilibrium concentration was reached after 150 minutes with rapid adsorption within the first 60 minutes. When the ammonium concentration in the water increases, high ammonium adsorption rates on LECA are observed. Adsorption mechanisms for oxyanions, such as phosphate, occur through both anion exchange and ligand exchange. Phosphate is adsorbed as an inner-sphere complex with the oxygen atom of phosphate bound directly to Al and Fe-oxides at the LECA surface. The levels of Ca, Fe, Al, and Mg in the substrate affect the degree of P adsorption by LECAs, with Ca showing the strongest correlation with P-sorption capacity. A positive correlation was found between P removal and the levels of CaO and Ca in the substrate. As a result, the low P removal observed in some LECA-based CWs could be due to the substrate's low Ca content. Clay minerals are known to possess high cation exchange capacity, making them efficient in removing heavy metals. This suggests that LECA has the potential for heavy metal removal. LECA has been used to remove Pb, Cu, and Cd from industrial wastewater and mining tailings. At neutral pH, LECA can remove some anionic pharmaceuticals, such as MCPA, oxytetracycline, and polyphenols, through electrostatic interaction. Moreover, compared to a hydrophilic compound such as caffeine, LECA showed better adsorptive removal for lipophilic compounds like oxybenzone and triclosan. LECA also exhibited effective adsorption of polycyclic aromatic hydrocarbons (PAHs), including phenanthrene, fluoranthene, and pyrene. LECA's ability to effectively remove high amounts of nitrogen is due to its high porosity and large surface area, which allows for better oxygen penetration, particularly when used as an upper layer. Moreover, the high porosity and specific surface areas of the LECA substrate enable better biofilm adhesion, which increases the biodegradation potential and makes it a suitable medium for organic matter removal. LECA's porous surface promotes biofilm development and bio-clogging, leading to successful bacteria immobilization. Moreover, LECA's high cation exchange capacity could aid in bacterial removal by improving adhesion. The clay minerals present in LECA could also alter the metabolic pathways of biofilm microorganisms encapsulating the granules by increasing cell division in *E. coli* when exposed to kaolinite (Mlih et al., 2020).

Figure 13. Expanded clay substrate/ Filter Media.

Source: (Wikipedia, 2023).

3.4.2 Organic

Coir

Coir is derived from coconuts and constitutes the fibrous husks of the coconut's inner shell. It is utilized in a diverse range of products, such as rugs, ropes, brushes, and even upholstery stuffing (Iannotti, 2022).

Coco coir refers to everything that lies between the outer coat and the shell of the coconut fruit. Coir comprises two types of fibers, namely brown and white. Brown coir is derived from fully mature coconuts and is stronger, but less flexible. White fibers are extracted from pre-ripe coconuts and are more flexible, but not as strong. When it comes to hydroponics, brown coir is predominantly used as it undergoes further processing after initial harvesting (Espiritu, 2022).

When coconut husk is utilized in biofilters, it generally contains 72.5% water and comprises 95% organic matter. Its specific surface area is around 0.75 m2/g, and it has a water retention capacity of 5.5g of water per gram of dry material (Pettit et al., 2018).

Under microscopic examination, coir fibers are found to consist of tiny hollow tubes. When dry coir is wetted, these tubes fill up swiftly and retain the water. Once the tubes reach their maximum capacity, any surplus water drains away. This drainage process draws in oxygen from the surrounding air and distributes it throughout the substrate. Furthermore, coir is regarded as "hydrophoric," a term derived from the Greek word "hydrophoria" meaning "water carrier," which is the antonym of hydrophobic and denotes a substance that has an affinity for water. Coir has a pH range of 5.5 to 6.5, which makes it highly compatible with plant growth. Coir has a prolonged lifespan because of the substantial lignin content in its constituents, taking years to decompose. As an organic substance, it is entirely biodegradable and can be reused as desired, making it an eco-friendly option (Larson, 2019).

Coir is often plagued by a prevalent issue of having a remarkably elevated salt concentration, primarily in lower grades. Consequently, coir with high salt content must be washed out before being employed (Nursery Management, 2007).

Coir pith, which is a slower filter media, was able to eliminate 92% of TSS, which is believed to be due to its smaller pore spaces. These smaller spaces create a stronger straining effect, which prevents solids from passing through the filters, resulting in a longer retention time for the greywater with pollutants. This longer retention time allows for a more efficient removal of pollutants due to the longer period of physio-chemical and biological processes occurring in the filter pores. Coir pith was also able to remove 75% of COD present in the greywater, and its structure allows for a longer retention time compared to perlite, resulting in a higher rate of bacterial degradation. This efficient removal of organic pollutants reduces the COD value of the effluent, and it is assumed that the trend is similar for the removal of BOD, with coir pith demonstrating a higher removal rate than perlite (Satheesh et al., 2021).

In another research, Slow media was found to be effective in removing Total suspended solids (TSS) by approximately 90%, and this can be attributed to the small pore spaces that increase the retention time, promote efficient straining, and facilitate particulate adsorption. The infiltration rate of Slow media initially declined but later increased after a 17-day drying period, most likely due to the creation of preferential flow paths resulting from media drying and cracking. The average removal rate for TN was 50%, ranging from 35% to 75%, with coir pith being the only Slow media to remove TN after the drying period, probably because of its high carbon content and sustained microbial community. TP removal rates ranged from 20% to 40%, indicating that retention time is crucial for overall performance, although it is unclear whether microbial activity or mechanical straining was responsible. The Slow media consistently showed an average removal rate of 70% throughout the entire experimental period and removal rates ranging from 60% to 100% in two initial tests for *E. coli* (Prodanovic et al., 2017).

Figure 12. Coir Substrate/Filter Media. Source: (Made-in-China, 2023)

3.5 Plants

Effective plant selection is a crucial aspect of designing green treatment systems for nutrient removal. For instance, certain plant species are required in rain gardens to meet specific nitrogen removal targets. Similarly, living walls, which use biofiltration systems, need resilient vegetation to remove phosphorus from greywater. The plants used in greywater treatment must withstand constant watering and prolonged drought during holidays. Green walls, on the other hand, require ornamental plants that meet high aesthetic standards, such as evergreen herbaceous perennials, lilies, grasses, ferns, and small shrubs. Unfortunately, there is limited information on the nutrient removal performance of ornamental plants, and more research is needed. While studies have evaluated the nutrient removal efficiency of ornamental plants in living wall systems, which are sand trenches with climbing plants and flowers, they did not study green walls, which have a different design. Plant selection involves considering various criteria, including but not limited to, their ability to tolerate sun exposure, uptake nutrients effectively, tolerate salt, sensitivity to water, and growth characteristics (Prodanovic et al., 2019).

Table 6. Plants suitable in green walls for greywater treatment

Plant	Reference
Cotoneaster dammeri	(Rysulova et al., 2017)
Blechnum spicant	
Carex oshimensis	
Ophiopogonplaniscapus	
Lonicera	(Boano et al., 2022)
Carex	
Hedera	

Today, a variety of plants are used for vegetated walls, but there are differences between choosing plants for wastewater purification and doing so for aesthetic reasons. It’s important to choose plants that can withstand waterlogged circumstances as well as environments with high nutrient levels and elevated salinity (Rysulova et al., 2017).

According to research by Boano et al. (2022), *Lonicera*, *Carex*, and *Hedera* were able to survive high moisture, temperature fluctuations, and solar exposure. There were no discernible variations in growth or health between groups fed with GW or TAP, according to qualitative analyses of the condition of the leaves and the growth of new seedlings for these three species. The preliminary test results showed that none of the plants selected for the green wall—*Lonicera, Carex,* or *Hedera*—were negatively impacted by GW, which was evident from the results.

According to Rysulova et al. (2017), there are several plant options suitable for treating greywater in green walls. One of these options is the *Toxocara dammeri*, which is a low, evergreen shrub that grows quickly and reaches an average height of 40 to 50 centimeters. This shrub can thrive in both moist and dry soil conditions. Another option is the *blechnum spicant* deer fern and hard fern, which are both evergreen and grow up to 50 centimeters tall. These ferns can grow in medium to moist soil conditions. The *Carex oshimensis* is also a good option, with its evergreen, grassy foliage that reaches 15 to 20 centimeters in height in moist soil. Finally, the *Ophiopogon planiscapus* is an evergreen perennial that grows in groups, reaching a height of 20 to 30 centimeters in moist, permeable soil.

4. Methodology

The methodology of this research paper is exploring the opportunities for the reuse of greywater using green walls. A basic overview of greywater and some conventional treatments used and green walls which include: the types of green wall designs and distinguishing its efficiency in treating greywater. Special emphasis is placed on the filter media on the functional performance of the green wall and for the growth of plants and their suitability. The aim of this work is a comprehensive description and arrangement of available obtained information from sources (i.e., available literature and scientific articles), which are related to the topic of the work of green walls, especially related to its treatment of greywater. The work is compiled and evaluated information in the form of literary research. The literature part of this thesis is focused on the technical parameters of green walls, the chemical characteristics of greywater, green wall design and its construction with technical parameters, and a general overview of filter media and plants in green walls. The practical part of this thesis is focused on summarizing the performance of the different types of filter media used in green walls for the treatment of greywater and its efficiency in the removal of pollutants.

5. Results

The result of this bachelor thesis is summarizing the information of research done on the filter media that are used in green walls, with attention to the importance of the treatment performances of different substrates and their capacity to treat different contaminants and to provide comparisons from different professional sources, on the best substrate suitable for use treating greywater in green walls.

Table 7. Treatment Performance of Coir and Perlite

Parameters	Filter Media	Removal Efficiency	Reference
COD (mg/l)	Coir	75%	(Satheesh et al., 2021)
TSS (mg/l)		92%	
COD (mg/[1])	Perlite	26%	
TSS (mg/l)		73%	
COD (mg/l)	Perlite	66.8%	(Mohammed Mountadar et al., 2013)
TSS (mg/l)		98.9%	
Turbidity (NTU)	Kaolinite/Perlite	76.92%	(El Machtani Idrissi et al., 2023)
COD (mg/l)		97.7%	
Turbidity (NTU)	Perlite	57%	(Majouli et al., 2012)
COD (mg/l)		94%	
COD (mg/l)	3:1 coir to perlite	53%	(Chua et al., 2020)
Turbidity (NTU)		54%	
TSS (mg/l)		41%	

Table 8. Treatment performance comparison of slow media and fast media.

Parameter	Filter Media	Removal Efficiency	Reference
TSS	Slow Media	90%	(Prodanovic et al., 2017)
TN		35% - 75%	
TP		20% - 40%	
COD		70%	
E. Coli		60% - 100%	
TSS	Fast Media	30% - 80%	
TN		Variable	
TP		10% - 20%	
COD		22% - 35%	
E. Coli		Variable	

Table 9. Treatment Performance of LECA substrate

Parameter	Filter Media	Removal Efficiency	Reference
Total N (mg/l)	2-4 mm LECA	82%	(Mlih et al., 2020), (Põldvere et al., 2009)
Total P (mg/l)		48%	
TSS (mg/l)		82%	
BOD (mg/l)		99%	
COD (mg/l)		70%	
HLR (59 mmd^{-1})		-	
HRT (4 days)		-	
Total N (mg/l)	20 cm LECA 13 - 15 mm	19%	(Lima et al., 2018)
Total P (mg/l)		18%	
COD (mg/l)		55%	
HRT (48-72 hours)		-	
Total N (mg/l)	LECA	70%	(Ozengin et al., 2016)
NH4-N (mg/l)		66%	
NO3-N (mg/l)		52%	
Total P (mg/l)		61%	

6. Discussion

As demonstrated in Table 7, perlite removed 73% of TSS while coir removed 92%. This discrepancy may be attributed to the smaller pore spaces in the slow-filter media. When the pores are smaller, the filter media has a greater ability to strain out solids, creating a restriction that prevents them from passing through the filter. This results in a longer retention time for greywater with pollutants to pass through the pores of the filter media. The longer the hydraulic retention time, the more likely the pollutants will be adsorbed onto the filters. Additionally, the small spaces between the pores trap larger TSS particles, preventing them from flowing out of the green wall system's outlet. Regarding perlite, which is classified as a fast media, the spaces between its pores are larger, allowing TSS to pass through the more loosely arranged pores. This means that higher concentrations of TSS can pass through the system without being filtered out. However, over time, the TSS will begin to fill the void between the pores, increasing the potential for TSS removal. This is because as TSS fills up the spaces between pores, the pore spaces will decrease, leading to higher concentrations of TSS being trapped in the layer of the pores and thus straining more TSS away from the greywater effluent. In terms of COD removal rate, perlite was able to achieve 26%, while coir pith removed 75% of the COD. The structure of the coir pith allows for a higher retention time compared to perlite. This longer retention time allows greywater with pollutants to spend more time within the structure of coir pith compared to perlite. With a higher retention time, pollutants can undergo longer physio-chemical (straining and adsorption) and biological processes in the pores of the filters. Similar to TSS, when organic pollutants are trapped in the filter, they spend a longer time within the pores, leading to a higher rate of bacteria within the filters that can cause the degradation of organic pollutants. The more organic pollutants are removed, the lower the COD value of the effluent. It can be assumed that the trend is similar for BOD removal of each filter media, where coir pith will exhibit a higher removal rate compared to perlite (Satheesh et al., 2021).

The best way to remove COD is by using a combination of coir and perlite in a ratio of 3:1, which leads to a COD removal rate of around 53%. The amount of coir used in the mixture plays a crucial role in the COD removal process, which is likely due to the biological degradation that occurs in the media. Using a higher proportion of coir can increase the retention time of water in the media, leading to better COD removal and leaching of organic particles. However, if the inlet pollutant concentration is low, the COD removal efficiency may be reduced due to the leaching of organic substances trapped in the media. In contrast, the removal of TSS from lake water decreases with an increase in the proportion of perlite in the media. In this study, the ratio of 3:1 perlite and coir were found to have the highest TSS removal rate of approximately 41%, while a ratio of 1:1 provides almost no TSS removal. This suggests that TSS removal is primarily driven by physical processes like filtration and sedimentation (Chua et al., 2020).

The filter media were classified as Slow or Fast based on their infiltration rate. Coir was categorized as Slow media, while perlite and expanded clay were classified as Fast media. A constant retention time of 17 minutes was maintained for the Fast media, while the Slow media were allowed to drain at their natural rate. The removal of total suspended solids (TSS) was high (around 90%) for Slow media due to their small pore spaces and higher retention time, which resulted in efficient straining and potential adsorption of particulates. In contrast, TSS removal for Fast media increased throughout the experiment due to the accumulation of sediment within the columns which reduced pore spaces and hence increased straining. On average, TSS removal rates for Slow columns were 50% and varied between 35 and 75% during the regular dosing. Nitrogen (TN) removal was negatively impacted by drying, with only coco coir being able to remove TN after the 17-day drying period, likely due to its high carbon content that sustained the microbial community. The nitrogen removal performance of Fast media was generally lower, and more variable compared to Slow media, with all Fast media types leaching nitrogen after high loading rates followed by three days of drying. Slightly higher phosphorus (TP) removal was observed in Slow media columns (20-40%) compared to Fast media (10-20%), but it is not certain whether the microbial activity or mechanical straining played a more significant role in this. This suggests that retention time plays an important role in phosphorus removal. Once the biofilm on the media had dried out during the dry periods, more surface area became available for the direct adsorption of TP. However, extended drying periods harmed the performance of all media types, while shorter drying periods did not have a significant effect. The Slow columns consistently removed about 70% of the COD throughout the experiment. The Fast columns showed a slight upward trend in their performance, starting with an average removal rate of 22% and finishing at 35%. The drying periods did not affect the removal of COD. While higher pollutant loading resulted in a slight decrease in treatment performance, the columns rapidly recovered following a return to the regular dosing regimen. The results suggest that COD reduction is likely driven by both physicochemical and biological processes due to the significant impact of retention time on removal (pointing to biological activity). The increase in removal over the time of the experiment suggests that natural clogging of the system increases COD straining. During the initial tests, the Slow media types demonstrated removal rates ranging from 60% to 100% for *E. coli*. However, the removal rates for Fast media types were positive, but they showed significant variability. The Fast media types showed positive but variable removal rates for *E. coli*, and stable removal was only achieved after high loading rates, indicating that a constant inflow concentration of *E. coli* is necessary for consistent removal. It is suggested that the initial *E. coli* removal is due to adsorption onto the media, but once the system developed a mature biofilm, biological processes such as adsorption to the biofilm, uptake, and biodegradation took over. The obtained data for pollutant removal was found to be independent of minor changes in flow rate during the experiment, as there was no significant correlation observed between the two variables. The two best filter media from this study was identified to be perlite and coco coir. However, both coco coir and perlite had their disadvantages. Coco coir, despite having the best treatment performance due to its high density and long retention time, was prone to rapid clogging. On the other hand, perlite had lower pollutant removal rates but had a superior hydraulic performance. It is important to note that both media were subjected to high greywater loading rates in both experiments (2-6 pore volumes per day) compared to field-scale systems, which are typically loaded with 0.2-0.3 pore volumes per day. Nevertheless, these systems remained effective for TN, COD, and *E. coli* removal (with somewhat weaker performance for TP removal), even after prolonged dosing periods. The perlite and coco coir columns were also unaffected by extended dry periods (Prodanovic et al., 2017).

Both studies have shown that coir had the best removal rate, due to its higher density and longer residence time but they are more vulnerable to clogging. Perlite showed lower pollutant removal capacity, but had better hydraulic performance and it can be surmised that a combination of these filter media would be the best option.

The LECA substrate is effective for removing organic matter due to its high porosity and specific surface areas, which promote biofilm adhesion and enhance biodegradation. A hybrid LECA CW system achieved almost complete removal of BOD (99%). Filtration and straining are not significant removal mechanisms in LECA-dominated systems due to the large granular size. However, LECA's porous surface enhances biofilm growth and subsequent bio-clogging, which facilitates effective bacteria immobilization. The high cation exchange capacity of LECA can also be beneficial for bacterial removal as it enhances adhesion. Additionally, the clay minerals in LECA, such as kaolinite, may alter metabolic pathways of biofilm microorganisms encapsulating the granule through the increase of cell division in *E. coli*. The P-binding capacity of LECA wastewater filters was increased to 1.1 g kg^{-1} on average with a loading rate of 100 L $m^{-2}d^{-1}$ and residence times ranging from 5 to 15 minutes. This high removal capacity for P is due to the hydraulic conductivity and adaptability of LECA to changing hydraulic loads. However, increasing the hydraulic loading rate to 239±7 L $m^{-2}d^{-1}$ with a hydraulic retention time of 140 minutes led to a maximum 66% increase in nitrate removal. Any further increase in the hydraulic loading rate had the opposite effect on the nitrate removal rate. the removal of nitrogen is limited when the temperature falls below 10°C. Moreover, nitrification does not take place at temperatures lower than 4°C. A decrease in water temperature from 20°C to 5°C led to a reduction in LECA's adsorption capacity by 24% to 64%, which increased with the size of the grains (Mlih et al., 2020).

As shown in Table 9, The physical and chemical characteristics of LECA are appropriate for use in treating domestic wastewater, specifically for removing bioavailable nitrogen species, organic matter, and phosphorus. The removal of organic matter that uses LECA as a substrate has shown a good P removal capacity with values ranging from 48% to 60% (Ozengin et al., 2016).

The main mechanism for removing turbidity and total suspended solids (TSS) in the green wall system was reported to be the physical straining of these particles in the filter media. The system was able to remove about 95% of the inflow turbidity (from 55 to 2.5 NTU) and 98% of TSS (from 91 to 1.4 mg/L). The green wall was able to remove approximately 90% of both *E. coli* and total coliforms, which is consistent with previous studies on green wall systems and other biofiltration systems that achieved similar levels of *E. coli* removal. Biological processes such as biofilm adhesion, predation by other microorganisms, and natural die-off are considered the main factors contributing to *E. coli* removal, in addition to plant uptake and the potential leaching of antimicrobial agents from the plants (Bakheet et al., 2020).

Under aerobic and unsaturated conditions, green wall systems promote bacterial uptake and transformation of available dissolved organic nitrogen (DON). TN removal was not affected by changes in hydraulic loading rate (HLR), but the performance of NOx and DON removal varied between good and poor-performing configurations. However, during high HLR, NOx levels remained the same as the inflow, likely due to the inability of the plants to effectively remove NOx, resulting in inflow NOx flow through. Increased water residence time during summer drying resulted in a significant drop in TN and TP removal performance, with an increase in particulate nitrogen in outflow samples. Organic phosphorus accumulation was hindered during the drying, leading to its transformation into FRP (filterable reactive phosphorus) upon re-wetting. However, some plants were unable to uptake it in time before it leached out of the system. During winter drying, lower variation in TP and FRP removal was observed between different plant species, suggesting lower plant activity. If space is not an issue, standard loading of 30 l/m^2 should be used to appropriately size the green wall system. However, if on-site greywater production is high and there is insufficient vertical space, an HLR of 60 l/m2 can be used with only a minor loss of treatment efficiency (Prodanovic et al., 2019).

7. Conclusion and contribution of the thesis

In this thesis, the general characteristics of greywater was focused, with the current conventional treatments being applied and the greywater regulations that are being applied in the EU and Czech Republic. Next, information was obtained on the green wall's history, benefits, and the multiple designs that are known throughout the world and state the applicability of which design is used for greywater treatment. The main contribution of this thesis is the summarizing of information and evaluation of the different performances and efficiency of substrates that are used as filter media for greywater treatment in greywater treatment and concluding the best substrate to be a combination of perlite and coir, due to coir's capability of long water retention which is beneficial to treat water and also for the growth of microorganisms that help treat contaminants, and perlite's ability due endure high hydraulic loading rate. Substrates used in green walls also has needs to be light weight, so substrates like sand that are heavy would not be suitable for a green wall system. The recommendation for the hydraulic loading rate for a green wall system, without any space issue is 30 l/m^2.

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