GREEN WALLS: AN OPPORTUNITY TO TREAT AND REUSE GREYWATER IN NEW ZEALAND.

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ABSTRACT

The national average household water use is 252 L/ p.e./d. The majority (60%) of this used water ends up as greywater and, combined with blackwater, is treated in wastewater treatment plants. Greywater is generated from household activities such as laundry, cleaning, handwashing, dishwashing, showering, whereas blackwater is from toilet waste. Greywater has a low pathogenic pollutant load compared to blackwater and so separating black and grey wastewater streams could offer numerous opportunities for greywater reuse such as irrigation, toilet flushing, and laundry, widely implemented overseas but minimally in New Zealand. Demands on freshwater consumption for outdoor irrigation (17%) and toilet flushing (18%) could be lessened by substituting freshwater with greywater for these activities. It would also reduce wastewater volumes, and associated collection and pumping costs, currently being treated in wastewater treatment plants.

Green walls provide multiple benefits including energy conservation, air purification, noise and thermal insulation and enhanced biodiversity. As living systems, they sequester carbon through photosynthesis. Additionally, green walls could be adapted to treat greywater at source, removing pollutants from the low pathogenic wastewater stream. Internationally, lab-scale green walls were demonstrated to remove organic matter (>90%), suspended solids (>99%), nitrogen (>85%) and phosphorus (>60%) from greywater. These early data are promising to support the principle of on-site wastewater treatment using green walls.

This paper reviews international practice on green walls capabilities and design considerations for treating greywater, with a focus on applying this knowledge to the national context. The effects of climate variables and native vegetation; potential for repurposing local waste substrates; as well as key legislative and cultural values in the New Zealand context; are discussed to suggest fit-for-purpose solutions to greywater treatment and reuse.

KEYWORDS: Greywater; Green Walls; Decentralized treatment; Nature-based technologies.

PRESENTER PROFILE

Moeen Gholami is a PhD candidate at the University of Canterbury investigating greywater treatment by green walls, focusing on the application of using additive manufactured media for the removal of greywater pollutants. He previously worked in industry for six years as an environmental expert on advanced oxidation processes and natural biofilters, with research interests on water and wastewater treatment technologies.

1. INTRODUCTION AND BACKGROUND

New Zealand is endowed with a large supply of freshwater sources from lakes, rivers and groundwater aquifers which have provided for individual and industrial (including agricultural) needs across the country. Nonetheless, the availability of and demand for freshwater fluctuates across regions due to factors such as geography and seasonal changes (Mellor, 2017). For instance, the summer months witness heightened demand for agricultural irrigation when water supply is lowest, leading to present and impending water allocation challenges (Mellor, 2017). This affects regional water distribution plans and in meeting escalating demands for freshwater supplies. Land use changes impact water quality and anthropogenic climate changes affect water supply security (Ministry-for-the-Environment, 2020), which amplifies these supply stresses. These challenges command a need to re-evaluate the risk of meeting water supply needs in the near future.

Greywater recycling is emerging as an effective strategy for conserving water and an opportunity for more efficient wastewater management, capable of yielding up to 50% savings in household water usage (Pradhan et al., 2019). Greywater, defined as household wastewater excluding toilet flushes, includes water originating from sources like bathtubs, showers, and laundry machines (Eriksson et al., 2002). Greywater has the potential to constitute as much as 75% of the overall domestic wastewater generated, equating to around 100–150 L/p.e./day in the EU and high-income nations (Boano et al., 2020). Furthermore, greywater contains lower quantities of nutrients, pathogens, and organic matter, compared to mixed domestic wastewater (Shaikh and Ahammed, 2020), making it suitable for treatment using more simplified decentralized systems. This integrated approach could not only reduce strain on freshwater resources but also lighten the load on wastewater treatment plants (Madungwe and Sakuringwa, 2007). Concurrently, it can reduce energy consumption incurred during wastewater collection and treatment, while also reducing the frequency of upgrading or development of new centralised treatment facilities (Mahmoudi et al., 2021). The local reuse of treated greywater for activities like toilet flushing and irrigation also fosters a circular economy (Boano et al., 2020).

Green walls, a type of vertical planter on buildings, have gained recent attention for their potential to treat greywater (Gattringer et al., 2016), in addition to their well-defined benefits including enhancing aesthetics, purifying air, reducing noise, supporting biodiversity, and mitigating urban heat island effects (Pradhan et al., 2019). Greywater has also been safely applied as fertigation (irrigation and fertilizer) to green wall vegetation, supplying carbon, nitrogen and phosphorus to the plants (Chung et al., 2021). However, the use of green walls for greywater treatment remains largely unexplored in New Zealand. This paper discusses the potential for greywater to be treated in green walls nationally in terms of technical and social considerations. Characterisation of greywater volumes, greywater quality, green wall types, costs and implementation challenges are discussed along with an explanation of the treatment mechanisms at play, societal views on reusing greywater and current regulations in the New Zealand context. This paper contributes to the knowledge of the opportunities for using green walls as a decentralised living wastewater treatment system that supports a more sustainable approach to integrated water-wastewater management.

2. RESULTS AND DISCUSSION

2.1. THE POTENTIAL ROLE OF GREEN WALL TREATMENT SYSTEMS IN NEW ZEALAND

There are a number of pressing demands on water resources and on related wastewater treatment infrastructure facing the country. Increasing demand for water consumption from residential users is attributed to overall population increases. From 1996 to 2012, New Zealand's population grew by 17%, leading to a 10% expansion in urban land area (Ministry-for-the-Environment, 2020). In terms of domestic water usage, households accounted for 17% of the country's allocated water use, while industrial activities accounted for 10% in 2017/2018 (Booker, 2017, Ministry-for-the-Environment, 2020). Simultaneously, New Zealand’s water and wastewater treatment infrastructure is aging, failing and under-sized for its current demand. Smaller communities are more vulnerable to these challenges given the cost of upgrades and/or new infrastructure from a smaller tax base. Opportunities to reduce the demand for potable water resources and increase the opportunity for water reuse, can offer more accessible solutions for such communities. Hence, the application of green walls offers a decentralized approach to greywater treatment, aligning with the needs of smaller communities. By adopting green walls for greywater treatment, these communities can achieve multiple goals at once: reducing the demand for conventional water resources and mitigating the strain on existing treatment facilities. Moreover, the visual and environmental benefits of green walls can contribute to an overall sense of well-being and community enhancement.

2.2. GREYWATER GENERATION IN NEW ZEALAND

Greywater originates from various activities and sectors, including residential households and commercial buildings like hotels, restaurants, and institutions such as schools and hospitals. The volume of greywater generated is influenced by population density, water consumption habits, and individual lifestyle choices, varying across regions in New Zealand. A 2022 Building Research Association of New Zealand (BRANZ) study examined water usage across 14 regions, revealing an average daily consumption of between 213 and 292 litres per person in winter and summer, respectively (Pollard, 2022). According to Figure 1, indoor water usage constitutes 90% of the total, with the remaining portion attributed to outdoor and miscellaneous uses. Showering was found to consume 31% of total water use in NZ, while toilet flushing accounted for 24%, hand basin taps 19%, washing machines 13%, outdoor use 7%, dishwasher 3%, leaks 2%, and undefined sources 1% (Figure 1) (Whittaker, 2022). For comparison internationally, in the USA, approximately 70% of water usage takes place indoors, with toilet flushing accounting for 24%, hand basin taps at 20%, showers at 20%, washing machines at 17%, leaks at 12%, and other uses at 8% (DeOreo et al., 2016).

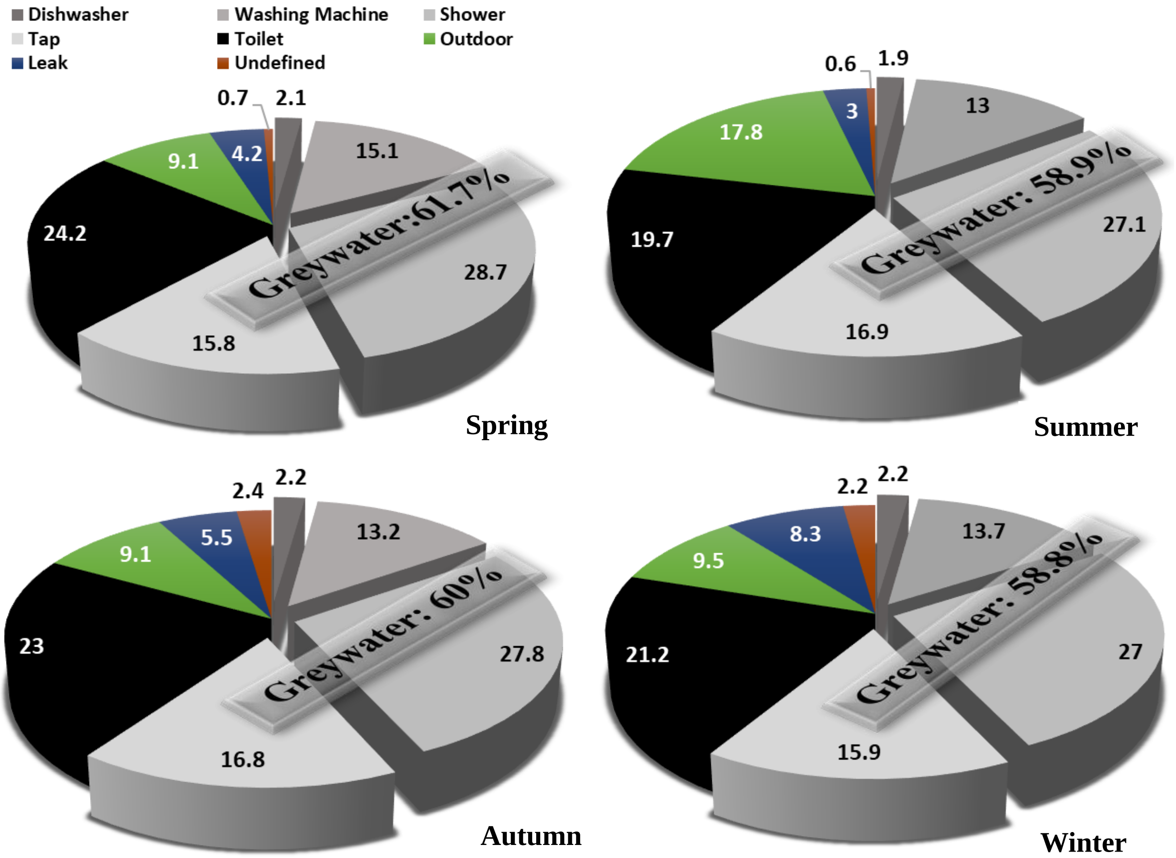

Figure 1. The distribution of daily water usage in New Zealand across various activities in different seasons. Adapted from Whittaker (2022).

Approximately 60% of the total water consumed in New Zealand households or institutions becomes greywater (Figure 1), resulting in an average greywater generation of 150 litres per person per day (L/p/d), higher than some nearby developed nations such as Australia (100 L/p/d). The remaining portion (approximately 40%) results from toilet flushing, outdoor uses, leaks, and unspecified origins. Figure 1 suggests that if greywater was reused for outdoor irrigation and toilet flushing, which constitute approximately 30-37% of the total water consumption, it could meet these water demands at the site of installation.

2.3. GREYWATER REUSE IN NEW ZEALAND

Nationally, a few local bodies are embracing water reuse. Some regions, like the Kāpiti Coast, have made it compulsory for all new homes to have an alternative non-potable (and non-reticulated) water supply, such as a rainwater or greywater collection system, specifically for outdoor irrigation, washing machines, and toilet flushing (Kapiti Coast District, 2017). Other regions, like Auckland, have permitted greywater reuse for toilet flushing with certain provisions (e.g. a small tank to store greywater for a short time, chlorine treatment to avoid build-up of harmful bacteria, a public water supply connection to the toilet as back-up if the tank is dry, a discharge connection from the tank to the sewer pipe, and building consent). While some councils such as the Central Otago District Council is currently investigating greywater reuse further (Central Otago District Council, 2022), others like Canterbury, Hawke's Bay, and Marlborough only encouraged the reuse of greywater without providing specific guidance, and the current rules for greywater are similar to blackwater (Siggins, 2013) which require adherence to strict disposal protocols and regulations to ensure environmental safety and public health. Currently, there is no update on greywater reuse for these areas, emphasizing the need for further exploration of greywater reuse systems in New Zealand and guidance on considerations to support their uptake.

Despite the lack of national-level regulations, standards or guidelines for greywater reuse in New Zealand, there are some international standards that could guide expected greywater quality requirements for the main pollutants of pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), total suspended solids (TSS), turbidity, total phosphorus (TP), total nitrogen (TN), and faecal bacteria. For example, based on the USA greywater reuse standard, the pH should be between 6-9, BOD_5 <10 mg/L, and be free of pathogens (Faecal coliforms) (USEPA, 2012). Table 1 summarises the minimum, maximum, and median microbial and physicochemical characteristics for greywater reuse guidelines and standards from different countries for different purposes (e.g. toilet flushing, urban reuse, irrigation, general). It is important to note that the quality specified is also linked to the permissible use(s) so countries that allow greywater use inside the building generally have significantly more strict requirements to protect public health than those that allow outdoor reuse. These ranges provide a snapshot for understanding international context on water quality standards for greywater reuse that could be applied in New Zealand.

Table 1. Maximum, minimum, and median concentrations of greywater pollutant reuse levels stipulated in standards and guidelines in different countries.

Parameter(s)	Minimum	Maximum	Median
pH	5 $^{(b)}$	9.5 $^{(d, b)}$	7.25
BOD_5 (mg/L)	5 (BOD_7) $^{(g)}$	30 $^{(e, h)}$	17.5
COD (mg/L)	50 $^{(h)}$	100 $^{(d, e)}$	75
Turbidity (NTU)	2 $^{(a, f, h)}$	10 $^{(e, b)}$	6
TSS (mg/L)	Free $^{(g)}$	30 $^{(c)}$	15
TP (mg/L)	2 $^{(d)}$	5 $^{(e)}$	3.5
TN (mg/L)	15 $^{(d)}$	45 $^{(e)}$	30
Anionic surfactants (mg/L)	0.5 $^{(e)}$	30 $^{(c)}$	15
Microorganisms (CFU/100)	ND $^{(a, b)}$	100 (Total coliforms) $^{(g)}$	50

(a) (USEPA, 2012), (b) (BSI, 2011), (c) (Vuppaladadiyam et al., 2019), (d) (Dal Ferro et al., 2021) and (185/2003), (e) (Dal Ferro et al., 2021), (f) (Cecconet et al., 2019), (g) (Chaillou et al., 2011), (h) (Asieh Sadat Malabashi, 2019). ND: Not Detectable.

2.4. GREEN WALLS FOR GREYWATER TREATMENT

The technical design of green walls for treating greywater involves a multi-faceted approach, addressing aspects such as biofilter configuration (e.g. depth, number of modules etc.), plant selection, substrate characteristics, irrigation needs, structural considerations, and operational parameters (e.g. hydraulic loading rates, pollutant loading rates, temperature, drying period, ease of maintenance).

2.4.1. GREEN WALL TYPES

Green walls are classified into green façades and living walls, each with distinct subtypes. Green façades comprise a single or limited number of planter beds with most of the wall coverage occurring from plant growth up the wall. These systems include direct (DGF) and indirect (IGF) systems, where DGF involves creeper plants adhering to walls without additional structures, though potential building damage and slow coverage are drawbacks (Manso and Castro-Gomes, 2015, Medl et al., 2017). IGF employs vertical climbing aids such as trellises or cables (Bakhshoodeh et al., 2022). Living walls in contrast, have many individual plants arranged in a grid-like pattern across the face of the wall. The two subtypes are continuous (CLW) and modular (MLW) living walls. MLW features separate containers with substrate and vegetation, arranged in a supportive structure, offering flexibility and easy replacement (Manso and Castro-Gomes, 2015). CLW uses mat-like materials, providing uniform coverage (Prodanovic et al., 2019a).

The selection of green walls varies based on the key objectives including; climate (e.g. temperature, shading, sun light, wind speed, humidity, evaporation rate), building function (e.g. commercial, school, hospital, hotel, residential), size (e.g. height, surface area, maintenance access), and its envelope materials. For thermal and noise insulation, living walls offer improved performance to facade green walls due to substrate insulation, rapid coverage of large surfaces, and uniform growth along the wall (El Menshawy et al., 2022). CLW can effectively and uniformly cover a larger area of wall than MLW. Living walls utilize the entire wall area for their biofilter component, in contrast to façades that primarily rely on ground level beds for treatment. Nonetheless, this expanded treatment area comes with additional costs. To provide aesthetics in all seasons, especially winter, MLW allow straightforward replacement of biofilter modules that have died or withered (Koch et al., 2020). MLW also provide more biodiversity, using a wide range of vegetation species. DGF is the lowest investment cost, maintenance cost, and ease of installation, as they do not need complex supporting structures and irrigation systems. This is especially beneficial for large buildings where these costs can quickly grow. The construction and maintenance of living walls involve more complex planter modules, irrigation systems, supporting infrastructure, specific growing substrates, and installation processes, than façade systems, resulting in higher overall costs (Vox et al., 2022). However, DGF is not suitable for walls with damage, such as cracks and may result in other building-related maintenance issues. Regarding nutrient and organic matter treatment from greywater, MLW is the most suitable due to its flexible design, significant substrate volume, and ample root space (Prodanovic et al., 2019a). Use of individual planters allows variation of plants and substrates targeting specific pollutant. Table 2 summaries the key design features by green facades and living walls commonly implemented (Mir, 2011, El Menshawy et al., 2022).

Table 2. Characteristics of green wall systems (Mir, 2011, El Menshawy et al., 2022).

Item(s)	Green Façades		Living walls	
	DGF	IGF	CLW	MLW
Type	Planted in soil	Planted in soil	Felt system	Planter box system
Rooting Space	Ground	Ground	Pocket	Planter box
Substrate	Soil/porous media	Soil/porous media	Felt/solid media	Soil/porous media
Supporting System	-	For plants	For module	For module
Air Cavity (mm)	0	3000 ≥ 50	~50	~50
Total Thickness (mm)	200	100	≤ 350	≤ 450
Maximum Greening Height (m)	30	30	Unlimited	Unlimited
System Weight (kg/m^2)	>5.5	> 4.3	100	> 150
Plant Species	Climbing plants	Climbing plants	Shrubs	Shrubs
Prefabricated / On site	On site	On site	Prefabricated/ On site	Prefabricated
Plant Life Expectation (years)	50	50	3.5	10
Maturity/Full Establishment Time (years)	~30	~30	< 1	< 1
Maintenance	Pruning	Pruning	Pruning/ replacement	Pruning/ replacement
Removal Efficiencies	-	TN:91% TP:67% BOD:98%	TN:26% BOD:95%	TN:93% TP:57% BOD:97%
Advantages	-Minimal additional structures -Natural appearance	-Enhances aesthetics	-Uniform coverage -Aesthetically pleasing	-Flexibility in plant arrangement -Easy replacement of individual modules
Disadvantages	-Potential building damage -Slow coverage	-The need for additional climbing aids -Climbing aids periodic maintenance	-Limited flexibility for plant selection -Complex irrigation	-High initial setup costs -Complex irrigation -High maintenance costs

Item(s)	Green Façades		Living walls	
	DGF	IGF	CLW	MLW
			-High maintenance costs	
Estimated Cost (NZD/m^2)	55-85	75-140	640–1375	735–1100

2.4.2. STRUCTURAL CONSIDERATIONS

Designing a structurally sound green wall treating greywater involves evaluating the load-bearing capacity of the chosen site or building. The weight of the plants, substrate, water, and associated components must be calculated to ensure the wall's stability and prevent any risk of collapse. This is particularly important in New Zealand given the high regional risk of seismic events and that living wall systems add loadings of 100 kg/m^2 or more. Specialized modular systems with lightweight materials and efficient water distribution mechanisms may be used to evenly distribute the weight and water across the wall, similar to concepts utilized in green roof systems more widely implemented to-date across the country. Adequate waterproofing and drainage systems are essential to prevent water infiltration into the building and ensure proper water circulation within the wall.

2.4.3. GREEN WALL BIOFILTER DESIGN

Green walls can be designed in single or multiple levels. Multi-level green walls require careful planning to ensure uniform water distribution across all levels. Gravity-driven systems or recirculating pumps are typically used to deliver treated greywater to the upper levels. Adequate drainage and overflow mechanisms are essential to prevent excess water accumulation and potential damage to the wall structure. The shape of biofilter can also be important, regarding their water distribution, vegetation support, and resilience to plant-withering during extreme weather or low flow conditions (Prodanovic et al., 2020). Using a merged design of biofilters where the top and bottom pots are integrated in one unit can provide better water distribution and reduce weight, vertical and exposed surfaces of the green wall, and total cost (Sakkas, 2013).

Biofilter size and depth emerges as a significant factor influencing the removal of pollutants by increasing contact time with treatment agents, optimizing vital processes like denitrification and phosphorous absorption (Thomaidi et al., 2022). Different biofilter depths ranging between 15 cm to 94 cm are reported for green walls treating greywater (Fowdar et al., 2017, Prodanovic et al., 2019a). Prodanovic et al. (2023) achieved 93% ammonia removal at a 700 mm depth, while depths of 300 mm and 150 mm attained average rates of 43% and 19%. Pradhan et al. (2020) showed that raising substrate depth from 15 cm to 40-60 cm significantly improved TN and phosphate removal (37% to 45% and 25% to 35%, respectively). However, deep biofilters or additional biofilters add extra loading on the supporting structure, increasing cost. The use of excessive units (such as a third level) can lead to cost escalation and undesired colour presence in the effluent due to material release from roots and substrates in the absence of more degradable organics from the greywater (Prodanovic et al., 2019a). Nonetheless, some studies showed that a third level can compensate the decrease in treatment performance during winter climates and as the system ages (beyond

2 years). This effect is particularly noticeable when dealing with high loading rates, which can result in increased variability and frequent occurrences of clogging phenomena (Costamagna et al., 2022).

The quantity and size of biofilters used in green walls treating greywater depend on the volume of greywater, which varies across different settings – for instance schools and offices may produce around 20 L/p/d and households 150 L/p/d (Fowdar et al., 2018). The sizing is influenced by the the hydraulic loading rate (HLR), pollutant concentration and the system's infiltration capacity (ranging from 200 to 400 mm/h to support plant growth and ensure proper drainage for media re-oxygenation). For instance, when considering an inflow of 50 L/p/d, utilizing an HLR of 5 cm/day, and having an influent BOD of 200 mg/L along with influent TSS of 120 mg/L, the suggested design surface area for BOD removal is 1 m^2/person, respectively (Fowdar et al., 2018).

2.4.4. SUBSTRATE SELECTION

At the heart of green wall design is the substrates, responsible for filtering, straining, and adsorption of pollutants as well as regulating water retention, and supporting vegetation and microbial biofilm. A well-designed vegetated substrate should have good particle size, pore size, porosity, air-filled porosity, specific surface area, cation exchange capacity, water-holding capacity, pH, electrical conductivity, and drainage properties (Koviessen et al., 2023). It should also be lightweight to prevent excessive loading on the wall structure (Prodanovic et al., 2018). Substrates may include a mix of organic materials (such as coconut coir, compost, and peat moss) and inorganic components (like expanded clay, perlite, and volcanic rock) to create an optimal growing medium for the selected plant species. The substrates' composition and depth are carefully chosen to target a wide range of pollutants and accommodate plant growth and water retention while avoiding waterlogging. Some studies suggested using a mixture of materials (Prodanovic et al., 2018), while others recommended substrates with distinct layers including top layer (sand-based ,90% depth), transition layer (well-graded coarse sand, 9% depth), and drainage layer (washed screenings, 1% depth) to control better hydraulic and removal performance (Fowdar et al., 2018).

Economical substrate options can be achieved by utilizing local waste materials. Agricultural/industrial/food wastes and by-products, such as nutshells, fruit stones, oyster shells, mussel shells, grass waste biochar, textile fibres, seeds, are generated in large quantities in NZ, and can act as effective growing substrates and adsorbents of water pollutants. The important factor in the selection of appropriate biowaste is its structural rigidity, low biodegradability and high reusability in order to increase the biofilter longevity and avoid clogging.

2.4.5. PLANT SELECTION

Choosing suitable plants with a robust capacity for nutrient removal is crucial for removing nitrogen and phosphorus compounds from greywater. Given New Zealand's temperate and variable climate an ideal plant should demonstrate resilience to temperature and wind fluctuations and thrive in environments with elevated organic and nutrient concentrations. Furthermore, the plants should possess an extensive root system that offer ample surface area, facilitating optimal oxygen levels for the growth of microorganisms and nutrient uptake (Vymazal, 2013). Apart from pollutant treatment efficiency, other vital factors in plant selection for green walls and roof systems include aesthetic appeal (evergreen, colourful), low maintenance, longevity, compact root growth, and lightness (Boano et al., 2020). In New Zealand, it will also be critical that the vegetation is approved for use and not pose as a biosecurity pest risk to native flora (and fauna), particularly given the increased chance of seed dispersion from plants located at elevation and possibly subjected to wind-funnelling.

Plants have different hydraulic behavior, depending on the morphology and characteristics of their root systems. For example, thick rooted-systems have higher filtration rates because of their macropores (Prodanovic et al., 2019a). Various vegetation species also exhibit differing adsorption capacities. Among greywater treatment options, *Carex appressa*, *Canna lilies*, *Lonicera japonica*, *Vitis vinifera*, and *Pandorea jasminoides* are noted for their effective TN removal (88-94%), while slower-growing species like *Strelitzia reginae* can cause pollutant leaching in effluent (Fowdar et al., 2017). Due to strict regulations aimed at safeguarding the local ecosystem, certain non-native plants like *Lonicera japonica* are prohibited from being purchased in New Zealand. *Carex appressa*, native to New Zealand, were also successful at removing phosphate from greywater in green walls (67%) likely due to their vigorous growth rates, extensive root systems, and longer root lengths.

2.4.6. HYDRAULIC LOADING RATES

Hydraulic loading rates (HLR) refer to the volume of water that can be effectively distributed and treated by the green wall system over a given period. Hydraulic loading rates need to be set to prevent waterlogging and ensure that the system can handle the amount of greywater conveyed. High pollutant removal can be achieved with HLR values between 50 and 60 mm/d. Higher HLRs (> 100 mm/d) might diminish the efficiency of pollutant removal efficiency due to reduced contact time for essential microbial transformations and physicochemical removal mechanisms (Fowdar et al., 2017, Prodanovic et al., 2019a).

2.4.7. CLIMATIC CONSIDERATIONS

Seasonal variations and temperature fluctuations play a significant role in the design and operation of green walls treating greywater. Temperature impacts vegetative water and nutrient uptake, affecting plant and microbial growth (Wang et al., 2022). Cold temperatures can hinder nutrient uptake rates and microbial activity responsible for nitrogen and organic matter removal (Fowdar et al., 2017). Research on various vegetation species utilized in greywater treatment in green walls revealed that nutrient removal efficiency was correlated to water uptake and transpiration rates (Prodanovic et al., 2019b). Selecting temperature-resistant vegetation and incorporating insulating materials can help mitigate temperature effects, maintaining microbial activity and enhancing pollutant removal efficiency during colder periods. It is crucial to consider plant adaptability to seasonal temperature variations in green wall designs to ensure optimal year-round performance. In colder climates, the system may require insulation or heating elements to prevent freezing and ensure continuous water circulation. In the New Zealand context, placement of treatment walls on north facing walls could reduce seasonal impacts.

The selection of hydraulic loading rates for greywater treatment systems is determined by climate, especially temperature; lower HLRs are preferred in temperate regions to reduce clogging risk due to slower microbial activity, whereas higher HLRs are advisable in tropical areas with heightened microbial processes, maintaining efficient treatment by preventing stagnation (Fowdar et al., 2018).

2.5. GREYWATER TREATMENT EFFICIACY

All green wall types are effective at removing nutrients including total nitrogen NO_X (NO_3^-+NO_2^-) and ammonia with removal efficiencies of >80%, 99% and 98%, respectively. However, these systems typically achieve less than 70% removal of phosphorus, which may be due to insufficient contact time and lack of anaerobic conditions in green walls. Concerning diverse mechanisms for nutrient removal, nitrogen is primarily eliminated through vegetation assimilation and microbial activity in the soil and root zones. Phosphorus is mainly removed through processes such as adsorption and filtration.

Some studies reported high removal efficiency of total phosphorus with over 85% and 91% using pretreatment systems for MLW (Sami et al., 2023, Eregno et al., 2017). However, the use of pretreatment systems can lead to increased operational, maintenance, and construction costs, as well as add complexity to the overall treatment system. Despite this, potential cost reductions may be achievable with their inclusion by applying higher loads, thus requiring less wall area.

In terms of organic matter, all green walls showed high BOD removal efficiency ranging from 83 to 98%. MLW with multi stages showed high COD removal efficiency of over 90% due to efficient contact time between pollutants and removal agents (e.g. substrates, roots, biofilm, etc) (Prodanovic et al., 2019a). Several removal mechanisms such as adsorption/filtration, biodegradation/biosorption, and phytoremediation, can play a crucial role in effectively reducing COD and BOD levels. Ramprasad et al. (2017) suggested that organic pollutants in greywater are mostly removed by microbial degradation and physicochemical adsorption. In addition, Pradhan et al. (2020) found that organic matter removal in green walls increased during treatment due to biofilm formation, resulting in enhanced filtration, biosorption and biodegradation. Also, Prodanovic et al. (2017) concluded that COD removal is mainly driven by both physicochemical and biological processes.

Turbidity and total suspended solids, such as sediments or particulate matter, are effectively removed by green walls, especially by MLW systems with removal efficiencies of 98% reported (Prodanovic et al., 2020). Plants' root systems act as natural filters, enhancing filtration provided by the substrate. However, suspended solids in the range of 1 to 10 μm may require additional filtration systems for effective removal.

Surfactants form a key component of most household products that contaminate greywater. Their removal appears more challenging than other organic components. For instance, removals of 71% to 83% using MLW systems is reported (Dal Ferro et al., 2021, Boano et al., 2020). Thus, the use of multi-stage green wall systems may be necessary for comprehensive surfactant removal, as demonstrated by Sami et al. (2023) who achieve 98% anionic surfactants removal. Similar to the removal of organic matter, the processes of phytoremediation, adsorption/biosorption, and biodegradation can potentially aid in surfactant removal (Dal Ferro et al., 2021). However, the specific mechanisms for surfactant elimination within green walls have not been extensively studied.

Green walls alone may not be sufficient to completely eliminate harmful microorganisms, especially at higher flow rates. Lakho et al. (2021) reported 100% *Escherichia coli* removal efficiency by a CLW at optimal flow rates, which reduced to 63% as flow rates increased (Lakho et al., 2022). In a separate study the maximum removal efficiency for *E. coli* by a multi-stage MLW system was 87% (Prodanovic et al., 2020). Based on these studies, it was hypothesized that the removal of pathogens could be mainly attributed to sorption/biosorption. However, these studies did not provide conclusive evidence regarding the specific mechanisms of removal, nor did they elucidate the roles of substrate, vegetation, and biofilm. In a study by Petousi et al. (2022), the effect of substrate type, substrate depth, and vegetation on the removal of *E. coli* by a green roof system was examined. The results showed that green roofs filled with 10 cm of perlite reduce total coliform concentration by about 0.4 log units while green roofs filled with 20 cm of vermiculite reduce total coliform concentration by about 1.2 log units. This was hypothesized to be from improved microbial degradation and predation processes because of an increase in contact time between treating agents and pathogens (Petousi et al., 2022). Additional disinfection methods, such as ultraviolet (UV) treatment or chlorination, are typically recommended to ensure the complete removal of pathogens (Bakheet et al., 2020).

2.6. RELEVANT CONSTRUCTION REGULATIONS

The construction and implementation of green wall greywater treatment systems in New Zealand involves obtaining approval from relevant national or local regulatory bodies for a combination of green wall and wastewater treatment aspects. Compliance with accreditation standards, including AS/NZS 1546.4:2016 for greywater treatment systems, ensuring effective and safe treatment practices; AS/NZS 4130:2018 for the appropriate material for plumbing and distribution within the system; AS/NZS 1319:1994 for clear communication of potential hazards; AS/NZS 3500:2021 for plumbing and drainage standards to ensure proper installation and functionality of the system; and AS/NZS 1547:2012 for on-site domestic wastewater management, guiding comprehensive planning and implementation, is essential (Fowdar et al., 2018). Local building regulations mandate the acquisition of planning and building permits, and approval from wastewater service providers is required if overflow connections are utilized. Designers and building owners must prioritize awareness of local legislative requirements during the planning and design stages to ensure successful approval and implementation (Fowdar et al., 2018).

2.7. COST ESTIMATION OF GREEN WALLS

Cost estimation for green wall systems encompasses both initial investment and ongoing operational expenses. The initial investment covers designing, constructing, and installing the green wall supporting structure and biofilters, alongside selecting and acquiring suitable vegetation and substrate materials. Additional costs include pipework for greywater separation, pumps, plumbing connections, filtration and disinfection systems, storage tanks for treated water, and monitoring equipment. Long-term operational costs involve maintenance, irrigation, and periodic replacement of materials. While literature offers limited cost assessments, studies highlight economic disparities driven by design and location. Reported capital costs for standard green wall systems range from $NZD 640 to 2195 per square meter (Pradhan et al., 2019), and in New Zealand, these costs can reach approximately $NZD 2,300 per square meter. Various factors contribute to this higher cost, including the limited number of companies working in this field, labour costs, and the transportation cost of materials. Kotsia et al. (2020) studied costs of using vertical flow constructed wetlands for greywater treatment in Greece, finding total costs, including initial investments (vegetation, substrate, tanks, pumps, disinfection, labour, etc.) and operations (power, maintenance, chlorine), of $NZD 3,901, $NZD 2,586, and $NZD 32,417 for multi-family buildings, single houses, and hotels, respectively. Substrate (19-29%) and maintenance (29-66%) are key expenses. Considering freshwater costs and sewage disposal, the Greek authors found the green technology payback period for hotels and multifamily buildings is approximately 2.5 and 4.7 years, while for single houses it extends to 16.6 years, when treated greywater is used for toilet flushing. This highlights the advantages of green technology adoption for apartments, offices, and hotels in comparison to membrane bioreactor (MBR) systems with a 70-year payback, particularly in areas with high water costs.

3. CHALLENGES TO GREYWATER REUSE IN NEW ZEALAND

Surveys by BRANZ conducted in 2014 have shown that over 70% of respondents found the use of greywater for irrigation and toilet flushing acceptable. For comparison, approximately 90% expressed satisfaction in using harvested rainwater for laundry, toilet flushing, and irrigation, and half viewed rainwater as suitable for drinking and cooking/food preparation (BRANZ, 2018). In Māori culture (and other indigenous communities), the health and wellbeing of communities are deeply intertwined with the health and wellbeing of wai (water) (Ministry-for-the-Environment, 2020). Furthermore, it is important to Māori that after wastewater is treated, it is then directed through land-based systems (Papatūānuku). It may be that green walls treating greywater can be part of the solution and support this value, though consultation is needed to further understand potential cultural implications.

Social barriers to integrating greywater systems in New Zealand buildings include high costs, lack of education and confidence in integrated water-wastewater management, uncertainty about public health risks associated with system operation and maintenance, and lack of regulations or clear guidelines. The financial aspect becomes a significant obstacle as homeowners assess the upfront expenses of system installation against potential long-term savings. Concerns about water quality, health implications, and waterborne diseases have been identified as major factors affecting perceptions of greywater reuse. Furthermore, the absence of clear regulations, along with sometimes burdensome legal rules, has constrained the adoption of greywater reuse systems. For example, in Auckland, as of the beginning of 2018, greywater systems had to adhere to the standards set in TP58 (subsequently replaced by GD06) (BRANZ, 2018), which pertains to on-site wastewater management system design and management. The restrictions in this document have been regarded as a barrier for implementation of greywater reuse systems. The widely varying rules between councils also limits common understanding and system development.

Navigating and overcoming these barriers can promote the wider implementation of greywater systems and sustainable water practices, benefiting both ecosystems and communities that depend on them. Government incentives, educational campaigns, and supportive policies can further encourage the implementation of greywater systems, promoting a sustainable and resilient water future for New Zealand.

CONCLUSIONS

Green wall systems for greywater treatment are innovative technologies with significant potential for sustainable greywater management in New Zealand. These systems, although emerging, offer a novel approach by integrating living plant walls into the at-source wastewater treatment process. However, several considerations are necessary to enhance their effectiveness and practicality in New Zealand.

Challenges include the initial high CAPEX costs associated with installation and complex plumbing requirements. A major challenge in New Zealand is the lack of regulations or consistent and clear guidelines regarding greywater reuse. Addressing public health concerns related to treated greywater is crucial, necessitating rigorous pathogen removal measures. Despite these hurdles, green wall systems offer remarkable opportunities in a climate of diminishing freshwater supplies and escalating conventional wastewater treatment systems. They provide environmental benefits through improved air quality, reduced urban heat effects, and biodiversity enhancement. The integration of green walls also presents an opportunity for research and innovation, exploring native plant species and treatment processes to optimize nutrient and pollutant removal. Additionally, these systems can serve as aesthetically pleasing urban elements, encouraging community engagement and education on integrates water-wastewater practices.

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