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Review

Perspectives of Utilizing Greywater in Agricultural Irrigation with a Special Reference to Vegetated Wall Agrosystems

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Abstract: With increasing urbanization, greywater, generated from domestic activities like bathing and washing, is a marginal water resource that can be valorized to meet irrigation demands and overcome water scarcity. This review paper delves into the characteristics and variability in greywater quality, highlighting the benefits of greywater reuse, such as water conservation, nutrient supply, and potential cost savings, as well as challenges like pathogen contamination and salinity buildup. Various treatment methods, including physical, chemical, and biological processes, are discussed concerning their effective use for irrigation. This paper explores the integration of greywater irrigation with vegetated walls, an innovative urban greening solution that offers numerous environmental and social benefits. The types of vegetated walls, their irrigation requirements, and studies involving greywater application in these systems are discussed. By synthesizing the current knowledge, this review article provides a comprehensive understanding of enhancing urban sustainability through the valorization of an otherwise wasted resource.

Keywords: wastewater; reuse resources; agrosystem; vegetated walls; urbanization; eco-humanism

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1. Introduction

Water is an essential resource for human health and prosperity. However, as time progresses, there is an exponential increase in the human population, leading to increased water demand. Water has become scarce in some regions and availability continues to change with climate, population, and development. It has been estimated that by 2050 one in every four people will suffer from water shortage [1]. The Mediterranean region of Europe has experienced a decline in water amounts leading to droughts, while regions of Eastern Europe have also seen a significant depletion in freshwater. Hence, the need for water conservation and water reuse strategies is essential; the demand and source side addresses the former while the latter focuses on the reduction in demand via the closure of the water cycle and promotion of circularity from the waste source to natural environments. Together, these strategies aim at one goal, which is to offer the sustainable management of water resources. Studies now also look at the behavior and attitude of people towards wastewater reuse. It is important to assess how willing people are to use water that is recycled. It is vital for people to show acceptance of recycled water before developing any wastewater treatment or reuse plan. Many disciplines are involved in tackling water conservation efforts, for example, political sciences, psychology, sociology, and economics [2,3].

There has been an increased interest in household water usage reduction and conservation. Researchers believe households can reduce water demand significantly. In households, water is primarily employed for sanitary needs, such as handwashing, showering, bathing, flushing toilets, and operating washing machines along with irrigation of gardens (Figure 1). It is noted that domestic water usage can be reduced by strategies such as pricing, appliances designed to use water efficiently, and policies/regulations. Certain factors are involved in the amount of water used by each household including but not limited to the level of education, awareness, religion, income, etc. For example, couples that have younger children are more likely to use greater amounts of water. Nonetheless, awareness is one of the key factors needed for water conservation and reduction [4].

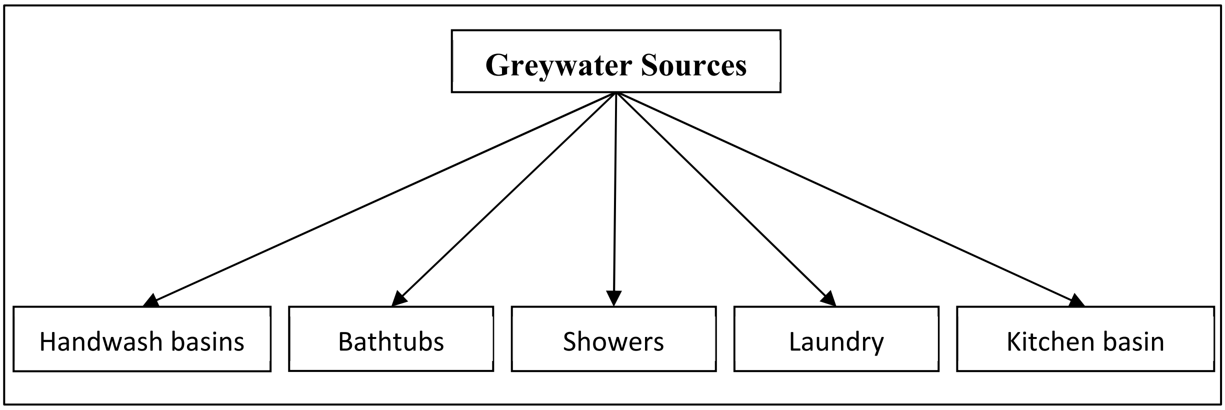

Figure 1. Greywater sources.

It is estimated that a person produces 15 L of wastewater a day in developing countries while for some of the wealthiest countries, it can be up to several hundred liters per person [5]. It is a low-strength wastewater with a high volume, showing great potential for reuse in many fields. Regions susceptible to water stress have a history of using greywater extensively in the past, and this is not a new practice. With the right amount of attention and prompt action, greywater can reduce the dependency of humankind on freshwater resources and even minimize the pollution caused by the release of untreated greywater into freshwater resources. Recycled greywater has been used in agriculture and toilet flushing [6]. Around 20 million farmers globally use either partially treated or untreated wastewater; countries such as the USA, Kuwait, Germany, Jordan, Tunisia, Italy, Malta, and Spain are all active users of greywater [7]. The utilization of greywater for agricultural applications offers environmental advantages by reducing the burden on freshwater resources and minimizing ecosystem contamination. However, the COVID-19 pandemic presented challenges to greywater irrigation due to the detection of viral particles in domestic wastewater. Fortunately, various treatment methods, as will be elaborated upon later, can effectively address this concern [8].

The emphasis on vegetated green walls and agricultural irrigation for greywater reuse applications is a calculated move to meet both established and contemporary water management issues. Due to the effects of climate change and growing water shortages, agricultural endeavors that use the bulk of freshwater extraction worldwide present a critical need for alternate water sources. Vegetated green walls, on the other hand, are a prime example of creative urban solutions that tackle a number of sustainability issues, such as urban heat reduction, energy efficiency, and water conservation [9]. Since both rural and urban areas share important technical issues about water quality standards, transmission networks, and treatment demands, a mix of these purposes offers insightful information across the spectrum. Additionally, their collaborative analysis facilitates the exchange of ideas between traditional farming methods and new urban technologies, resulting in thorough environmentally friendly water conservation tactics that are especially pertinent as the world's population grows and water resources face greater stress.

Greywater composition is dependent upon the lifestyle of the people and the chemicals they choose to use for their laundry, bathing, and cleaning. The distribution systems and water supply also play a vital role in the characteristics of greywater. Spatial and temporal factors also affect greywater composition along with the biochemical degradation of certain compounds, storage, and transportation mediums.

Using Web of Science, Scopus, and Science Direct, among other important scientific search engines, the literature review was limited to studies produced between 2000 and 2024. The systematic review procedure began with general search phrases pertaining to vegetative walls, greywater recycling, and crop irrigation, which at first produced more than 400 papers. About 155 core articles that serve as the foundation for this study were assembled after the papers identified in the search results were methodically whittled down according to their applicability to our particular target areas. Peer-reviewed publications with thorough case studies, quantitative information, and methodical evaluations of the applied results were given precedence. To provide a fair portrayal of study findings, the chosen literature covers a variety of geographic areas and incorporates both laboratories and field investigations. This strategy preserved the emphasis on the applications we had selected while enabling us to recognize important trends, obstacles, and possibilities in greywater applications with regard to agricultural irrigation.

Characteristics of Greywater

A wide array of substances and components can be determined within greywater. The composition of greywater can include but is not limited to organic compounds and salts along with nitrates and phosphates and their derivatives (Table 1). Xenobiotic organic compounds and microbes such as *Salmonella* and fecal coliforms might also be present [10]. Researchers also find heavy metals such as Ni, Pb, Cu, Cd, Ar, and Hg, as well as aerosols, pharmaceuticals, beauty products, and pigments [11]. Moreover, studies have shown how complicated the composition of greywater has become with time [6]. Furthermore, it is important to take note of the health hazards involved in dealing with untreated greywater due to microbial contamination [12].

Table 1. Characteristics of greywater.

Characteristic	Range	Reference
Physical Characteristics		
Temperature	14–35 °C	[6,13–15]
Turbidity	11–444 NTU	[6,16,17]
Total Suspended Solids (TSSs)	32–537 mg/L	[6,18,19]
Total Dissolved Solids (TDSs)	712–990 mg/L	[14,20]
Chemical Characteristics		
pH	7.09–8.3	[18,21,22]
Chemical Oxygen Demand (COD)	130–770 (mg/L)	[18,20,23]
Biological Oxygen Demand (BOD)	62–460 (mg/L)	[18,23]
Nitrogen (N)	4–74 mg/L	[13,22,24]

Table 1. *Cont.*

Characteristic	Range	Reference
Physical Characteristics		
Phosphorus (P)	0.8–15 mg/L	[22]
Fats, Oils, and Grease (FOG)	50–195 mg/L	[20,24,25]
Surfactants	0.1–20 (mgLSS/L)	[22,26]
Chlorine Residuals	10–40 mg/L	[27,28]

Undoubtedly, the environmental advantages of greywater reuse are evident. Nonetheless, the considerable variation in greywater quality across different locations and over time poses a significant challenge to the development of effective treatment systems. For instance, the volume and concentration of greywater vary from place to place, and specific factors other than just location contribute to this variation. These factors include the activities of residents, the usage of chemical products, and living standards. To begin with, the variation in flow determines the treatment type for greywater recycling in communities and households, the mode of flow seen is diurnal just as in domestic wastewater [29]. Significant variation was reported on weekdays and the weekend with the greatest flow recorded between 17:00 and 22:00 h and 07:00 and 10:00 h. Late night and early afternoon were times when the flow was low during working weekdays. During late afternoon, there was an observed increase in the flow rate of greywater, which may be due to people having lunch. It was observed that in households, hand basins and showers served as the primary sources of greywater. The highest Light Greywater (LGW) flow was identified to occur between 18:00 and 23:00 h, contributing to 50% of the total greywater generated in a dormitory [30]. A minor increase in LGW was reported during night hours at dorms, which was due to students studying late hours [30]. Regarding the sources of greywater flow, significant fluctuations were observed throughout the day. In the morning, from 5:00 to 11:00 a.m., there was a predominant discharge of 30–60% of Light Greywater (LGW), followed by a sharp decrease during the rest of the day to 20–40%. As mentioned earlier, showers, hand basins, and baths experience a substantial increase in greywater flow during the morning hours. Conversely, kitchen and laundry sources, which contribute significantly to greywater flow, exhibit less variability in their discharges [29]. Minimal variations were observed in the flow characteristics of greywater, both in terms of flow rate and timing, between urban and rural areas. The temperature of greywater, on the other hand, varies according to the flow pattern, with lower flow patterns associated with lower temperatures.

Antonopoulo et al. (2013) [19] highlighted that diverse household sources contribute varying levels of pollutant load and greywater volume. This aspect has provided researchers with the opportunity to examine the variations in greywater characteristics from one country to another. This research, conducted in Greece, a region grappling with water scarcity, focused on the production of greywater. The absence of standardized protocols for greywater characterization underscores the pressing need for the development of effective treatment systems and greywater reuse strategies. The study's findings revealed significant variations in pollutant levels among different households in Greece, with 58% being characterized as greywater and 42% as blackwater. Additionally, greywater from bathtubs and showers exhibited similar pH levels, ranging between 7.07 and 7.22, with TSS concentrations at 60 mg/L and total Chemical Oxygen Demand (COD) concentrations at 399 and 335 mg/L. In contrast, greywater from kitchen sinks displayed distinct characteristics compared to showers and bathtubs, including lower pH levels and higher COD and TSS concentrations, ranging from 775 to 299 mg/L. It is worth noting that greywater from the kitchen is typically recognized as the most contaminated [19].

In a study by Bakare et al. (2017) [10], greywater variability was tested in Durban, South Africa. This is a semi-arid region where precipitation rates are low and evapotranspiration rates are high, making water scarce. Greywater samples were taken from 75 different households in an attempt to characterize the water and provide a treatment system. The findings reaffirmed that the kitchen stands out as the primary source of contamination. In this regard, the pH values in the kitchen were notably lower compared to those in the bath and laundry sources, registering at 6.25, 9.58, and 9.24, respectively. The reason for this could be that kitchen greywater contains food/oils, which are needed for greywater degradation along with organic compounds fermenting in transit, releasing volatile organic compounds (anoxic conditions are preferred). The high pH coming from laundry and baths is due to the alkaline nature of the detergent/soaps used; the conductivity values were 320, 680, and 156 µS/cm, respectively. This shows that kitchen and laundry have better conductivity than baths. Good conductivity is beneficial for reuse in irrigation provided a limit is not exceeded. Other parameters showed similar results throughout the literature such as low oxygen demand but high carbon dioxide amounts. In a separate investigation carried out by Bodnar et al. in 2014 [31], a qualitative analysis of greywater was undertaken in the Northern Great Plain Region of Hungary. The outcomes mirrored the findings reported by Bakare et al. in 2017 [10].

In summary, greywater's properties show a dynamic and intricate wastewater stream that captures the nuances of contemporary home life. The great variation in its makeup, which is impacted by anything from household cleaning practices to personal care product preferences, highlights how difficult it is to create standardized treatment plans. On the other hand, this heterogeneity also emphasizes how specific home initiatives might enhance the quality of greywater. Greywater's nutritional content, which includes nitrogen and phosphorus, has two drawbacks. These substances can help plants develop and lessen the need for synthetic fertilizers, but if they build up in the soil over time and are not adequately handled, they may cause environmental problems. This dichotomy highlights the necessity of a comprehensive, long-term strategy for greywater reuse in agriculture.

2. Greywater Treatment

Physical filtration systems form the cornerstone of greywater treatment in urban settings. Among the basic and most frequently used procedures for preparing greywater for agriculture is physical treatment, which falls under the primary treatment category. Such procedures entail the mechanical elimination of pollutants and residues from greywater through the use of distinct mechanical obstacles and procedures.

Physical treatment techniques are frequently seen as inexpensive, low-tech options that are simple to utilize in a community, and some of the common ones are found in Figure 2. Some of the more popular physical treatments for greywater within the pretreatment stage are filtering and settling. To eliminate particulates, silt, and other contaminants, greywater is often passed across/through a filter media. Sand, gravel, and other kinds of composite polymers such as active charcoal or zeolites may all be employed as a filtration medium [32,33]. Settling and filtering techniques are efficient in clearing floating particles, biological material, and certain microorganisms from greywater when used as physical treatment procedures.

Biological treatment processes have emerged as particularly effective in urban applications, especially when integrated with existing infrastructure. There are multiple methodologies involving biological treatment, which include constructed wetlands, biological aerated filtration (BAF), sequencing batch reactors (SBRs), membrane bioreactors (MBRs), trickling filters, and rotating biological contactors (RBCs) [34–42]. The thorough assessment of artificial wetland systems as pre-treatment facilities by [43] displayed exceptional efficacy in the removal of contaminants. According to their findings, the BOD consistently dropped by more than 96%, while the TSSs dropped by about 94%. Temperature emerged as a major element in treatment efficiency, and the efficacy of these biological systems varied significantly depending on the climatic circumstances. Proper equipment selection, consistent monitoring, and the use of adaptive management approaches are critical to system performance. According to the body of research, well-planned and managed greywater treatment systems may support larger urban sustainability objectives while supplying reliable, exceptional irrigation water for vegetated wall applications.

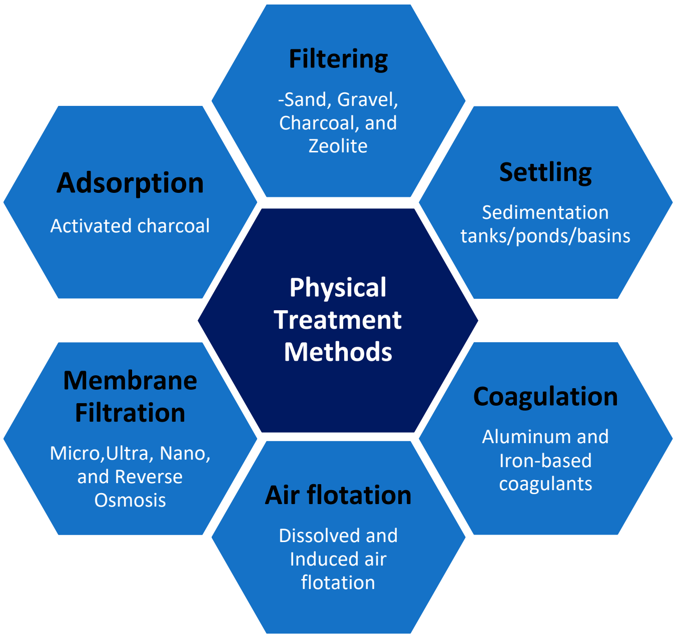

Figure 2. Physical treatment options for greywater.

3. Benefits and Challenges of Greywater Irrigation

The agricultural sector stands as the leading consumer of freshwater resources, exerting significant pressure on our planet's freshwater resources. The shortage of freshwater resources has spurred the interest in exploring the utilization of greywater for soil application [44,45]. In this region, approximately 70% of freshwater is utilized in agricultural fields [46]. Arid regions such as Jordan [47] are using greywater adequately for crop irrigation [44]. Faraqui and Al-Jayyousi (2002) [48] conducted research where the use of greywater in agriculture helped alleviate poverty as community members learned skills such as food preservation, responsible irrigation, and gardening skills. Furthermore, in another study conducted by Roman et al. (2007) [49], greywater was used in vegetable irrigation in Lima, Peru. The results showed a better urban environment and reduced poverty. Reduced health problems were seen along with low-cost food being available in the market. Other literature that used greywater in smaller crops and gardens also showed similar positive impacts regarding cost reduction and food security.

3.1. Benefits of Greywater Irrigation

Greywater irrigation has shown many positive benefits in gardens [50]. From increasing the plant growth to improving the crop yield without any adverse effect on the crop quality [51,52]. Additional support to the growth and production of crops can be applied due to the additional nutrient loading that greywater can provide. Garden soil alkalinity increases if irrigated with greywater, in addition to the nutrient supply and salinity level balance of the soil [44].

The implementation of greywater recycling marks a significant stride towards ensuring the preservation of indispensable freshwater reserves. It accomplishes this objective by mitigating reliance on drinkable water for irrigation purposes, hence diminishing the overall demand for pristine water sources [53]. The significance of this is especially pronounced in dry regions confronted with chronic water shortages. Additionally, greywater contains vital nutrients and organic substances that greatly benefit soil quality by significantly amplifying its fertility and encouraging vigorous plant development. Moreover, applying greywater to crops can lessen dependency on synthetic fertilizers, thus reducing agronomy's ecological footprint [54]. In essence, the adoption of greywater utilization within agriculture emerges as a sustainable strategy aimed at enhancing water use efficiency, fostering soil vitality, and bolstering environmental integrity in irrigation is one that must be promoted due to the clear benefits observed.

3.2. Challenges of Greywater Irrigation

While the use of greywater in irrigation presents numerous benefits, there are also several challenges and considerations that need to be addressed. One of the main challenges is ensuring proper treatment of greywater to remove contaminants and pathogens. This is crucial to prevent any potential health risks associated with the use of untreated water. Without adequate treatment, greywater can potentially introduce harmful substances and microorganisms into the soil, posing risks to both human health and the environment [55,56]. Another consideration is the potential impact of greywater on soil quality. Studies have found that untreated greywater can increase the presence of oil, grease, surfactants, and bacteria in soil [56,57]. These contaminants can lead to soil hydrophobicity, reduced soil hydraulic conductivity, and dispersion of soil aggregates. In addition, the potential for enhanced contaminant transport is also a concern when using untreated greywater for irrigation [58]. Investigations of trace elements present in crops irrigated with greywater are essential to assess the safety of the food output or any related health concerns. Unfortunately, there is a lack of health risk assessments for the impact of greywater on crops. If such an assessment existed and showed little to no risk, then it is plausible for rural regions in arid–semi-arid areas to use greywater for small-scale farming.

Among the many factors that affect plant growth concerning greywater is phosphorus levels, which limit sustainable irrigation with greywater. The lack of governmental laws and inappropriate consumer behaviors do not allow products with low phosphorus levels to be made available in the market [59]. The consequence of such actions leads to phosphorus being leached into soils by greywater. High phosphorus levels increase freshwater eutrophication. Eutrophication is a phenomenon that results from excess nutrient leaching, in particular excess phosphorus, into aquatic systems and lakes. This type of over-enrichment leads to algal blooms where oxygen is depleted leading to the death of aquatic life [60]. Phosphorus found in greywater is of two types: sodium tripolyphosphate or potassium phosphates [61]. They are often in detergents with the role of builders, which enhance washing performance by reducing water hardness. This is achieved by the effective binding of the builders to magnesium, calcium, iron, and manganese ions. As phosphorus uptake by soil occurs, it is absorbed by aluminum/iron oxyhydroxides along with aluminosilicates by ligand exchange. The level of phosphorus that a soil can absorb is directly proportional to the concentration available. When phosphorus sorption sites are all saturated and equilibrium is attained, any more irrigation leads to a net release of free phosphorus, which meets the soil surface via water runoff or goes deep into the soil profile, meeting groundwater. This is what leads to eutrophication and contamination of the environment.

A proposal by researchers builds upon previous studies where the quality of greywater used has a direct relationship with irrigated soil-related phosphorus loss in addition to the physiochemical properties of the soil involved. In this approach, a phosphorus buffering index to the Colwell P ratio is determined, which is altogether defined as the Phosphate Environmental Risk Index (PERI). If the ratio exceeds 2.0, there is a great risk of P loss from soil [61]. It can be seen that in both studies the threat of phosphorus leaching is high and agreed upon by scientists. Being well aware of such a topic, it is important to raise awareness and inform residents of households how much impact their products have on greywater. The need to protect the environment comes with education and teaching. It is evident that industries and markets do not cater to producing products that can reduce P levels nor are there any strict laws and regulations imposed by the government on its subjects to take mindful action and better themselves. Finally, it is the action of organizations that can lead to making sure greywater reuse can benefit the environment optimally. This is not only of interest to a scientist but also to all individuals who value and celebrate a safe environment [59].

In conclusion, there are a variety of intricate advantages and difficulties associated with using greywater for irrigation. The main benefits include substantial water conservation, less strain on freshwater resources, and the possibility of nutrient recycling, which can lessen the need for artificial fertilizers. In areas with limited water resources, greywater irrigation can also help with urban greening and increased food security. These advantages are, however, offset by a number of difficulties. It is challenging to treat and apply greywater consistently due to its variable composition. Pathogen contamination, soil salinization, and the gradual build-up of toxic compounds in soil and plants are all possible causes of damage to plants and soil [62,63]. Furthermore, challenges with public image and the absence of uniform standards may make widespread adoption difficult.

4. Economic Analysis of Greywater Irrigation Systems

The implementation of greywater irrigation systems presents both economic challenges and opportunities that must be carefully considered when evaluating their feasibility. First off, installing irrigation and greywater treatment systems might need a sizable upfront cost. This covers the expenses related to setting up infrastructure for distribution, treatment centers, and collecting systems. But these initial expenses have to be balanced against the long-term advantages of using less freshwater and maybe saving money on water bills. The financial advantages of reusing greywater can be especially significant in areas with limited freshwater resources when access to freshwater is restricted or costs are high.

The economic feasibility of greywater irrigation systems is intimately connected to the extent of use. Economic systems of magnitude may assist large-scale systems, such as those used in community or agricultural contexts, potentially lowering the cost of treatment and distribution per unit. On the other hand, small-scale systems, like those for individual homes, could be more expensive overall, but they can still be profitable since they save money on water bills and increase the amount of food produced for domestic use. The study by [59] highlighted the potential for significant water conservation through greywater reuse. Their research demonstrated that four irrigated plots cumulatively used 1.6 million liters less freshwater over four years compared to conventional irrigation methods. This substantial reduction in freshwater usage translates directly into cost savings, particularly in regions where water prices are high or rising due to scarcity.

Finally, the wider socioeconomic and environmental advantages of greywater reuse should be considered in the economic analysis. Even though they might be hard to put a number on, things like increased water security, less demand for freshwater resources, and possible upgrades to urban green spaces can all have a big impact on the economy indirectly by improving people's quality of life and environmental sustainability.

The potential for water conservation, decreased fertilizer use, and increased agricultural productivity suggest that greywater irrigation systems can be economically viable under the right conditions, even though a thorough economic analysis of such systems would require specific local data and calculations. The development of more reliable economic models that can take into consideration the many direct and indirect costs and advantages connected to greywater reuse in agriculture should be the main goal of future research.

5. Safety Considerations

If not adequately treated, the bacteria, chemicals, and pollutants found in greywater might represent a threat to human welfare. To reduce the hazards connected with using greywater for agriculture, it is crucial to adopt the proper precautionary measures. The possibility of disease transfer constitutes one of the biggest concerns. Many microbes, such as bacteria, viruses, and parasites, may be found in greywater and can cause conditions and illnesses in both people and wildlife [64]. To reduce the danger of disease transfer, it is crucial to guarantee that greywater is treated appropriately and sanitized. There are several methods to ensure pathogen removal from greywater which include disinfection via chlorination or ozonation, exposure to ultraviolet light [65], and heat treatment via boiling or pasteurization [66], and even filtration via sand beds [67]. It is crucial to remember that several techniques may be employed to efficiently eliminate microorganisms from greywater. Every disinfection device must also be carefully maintained and monitored to guarantee that germs are being removed efficiently. Another significant issue is chemical pollutants. Surfactants, housekeeping solutions, and personal hygiene items are just a few of the chemicals that greywater may include. These substances not only pose a risk to human health but also to the environment. As a result, greywater that includes dangerous compounds or heavy metals must be avoided or adequately treated before usage. In addition, it is critical to adopt the right irrigation procedures to reduce any possible health hazards. For instance, using greywater on plants intended to be consumed fresh, such as fruits and green vegetables, is not advised because they are highly vulnerable to coming into contact with pathogens such as fecal coliforms, which are found within untreated greywater [68]. Furthermore, using greywater in locations with stagnant water is not advised since it might attract mosquitoes and other disease-carrying pests [69].

Regulatory Considerations

Municipal and federal governments have legislation surrounding the use of greywater for irrigation, and these restrictions might change depending on where the greywater will be used. Greywater recycling might not be controlled at all in some places but may be heavily regulated elsewhere. The varieties of greywater that might be recycled, the degree of processing necessary, the administration techniques, the dimensions and kinds of irrigation systems, and the offsets from structures, perimeters, and freshwater bodies are just a few of the topics that guidelines may tackle [65]. When planning and putting up a greywater watering network, it is essential to verify regional laws. Engaging with a professional contractor or architect, acquiring permissions or licenses from governmental bodies, and making sure the network is correctly built, implemented, and operated are all examples of ways to comply with regulatory standards. It is critical to remain current on regulatory regulations because they could evolve as time passes. Before the establishment of the network, it is also necessary to explain greywater recycling to the regular populace. Then, to promote the nation's growth prospects, the equipment for the greywater filtration infrastructure and budget must always be bulletproofed. The program's economic feasibility will be investigated, the existing greywater reuse framework and its alternative solutions will be analyzed, and the technical, fiscal, and economic effects of integrating channels to a decentralized greywater reuse and processing facility rather than a consolidated effluents treatment facility will be assessed. Not to mention, the organization necessitates research into the economic feasibility and public acceptability of modifying pre-existing structures to add greywater recovery capabilities. For example, a study by [70] investigates the constraints of greywater reuse in Oman with a large majority of the public siding with greywater reuse for irrigation. However, a large majority also stated health, religion, and ecological degradation as reasons to not adapt greywater for potable usage. Furthermore, Omani legislation at the time did not even differentiate between greywater and blackwater. Greywater reuse necessitates the separation of greywater from untreated wastewater, which is not a common engineering procedure in many nations and necessitates infrastructure upgrades. Based on the facility and equipment sophistication, this conversion differs significantly in labor and cost. On a greater scope, extensive greywater transfer might compromise wastewater gathering and processing since less wastewater is redirected for purification and more pollutants and aggregates are present.

6. Effects of Greywater Irrigation on Crop Yield and Quality

6.1. Plant Selection and Requirements for Greywater Irrigation

In order to provide effective and sustainable farming techniques, species choice and criteria for greywater cultivation are essential. Greywater includes various pollutants, including salts, organic waste, and minerals, that, if not adequately controlled, can harm crop development and welfare [71]. It is crucial to consider the species' salinity resilience, nutritional ratios, and water demand while choosing the right vegetation for greywater cultivation since an imbalance in any essential ratios may lead to damage such as leaf necrosis [72]. Succulents, aquatic/marine plants, vines, and other halophytes along with species such as heliconia and cattails that are utilized in wetland treatment are good candidates for greywater treatment since they are salt-tolerant and demand minimal watering [43,73,74]. Furthermore, since it is unclear if eating produce cultivated with greywater has any health hazards, it is crucial to not water edible vegetation with it. Concerning species variety, it is critical to take into account every crop species' unique needs in terms of watering rate, length, and quantity. Greywater farming methods must be made to deliver the right quantity of water to vegetation without overwatering or underwatering, which can strain vegetation and stunt development [75]. Effective greywater irrigation also depends on good land development. Greywater can raise the hydration content of the soil, causing waterlogging and root damage, and thus the earth has to be drained efficiently. By introducing earth with organic material, one may help it retain more water, have a better foundation, as well as provide crops with more nutrition. In order to promote optimum crop development and condition, it is crucial to constantly assess plant well-being and development and change watering strategies as needed. In order to make up for any nutritional deficits, this may entail altering watering regularity, quantity, or time in addition to fertilization of vegetation as necessary.

6.2. Observation of Crop Yield and Quality

In areas with limited water resources, using greywater for agricultural irrigation is becoming more and more popular as a sustainable approach to water management. Comprehending the effects of greywater irrigation on crop productivity is essential for maintaining food security and agricultural sustainability as freshwater resources become increasingly scarce. This section looks at how greywater irrigation affects crop quality and productivity, showing the advantages and disadvantages of this method. Greywater may supply crops with vital nutrients and organic matter since it usually has lower levels of pollutants than blackwater. Greywater's diverse makeup, which might include microbiological and household chemical contamination, can, however, also be hazardous to plant development and food safety. Because of this, greywater irrigation's impacts on crop output and quality can be intricate and varied.

Studies have demonstrated that the effects of greywater irrigation on agricultural productivity can vary. An indoor study was carried out by [76] to investigate the impact of greywater irrigation on the development of silver beet (*Beta vulgaris*). Four irrigation treatments were used in their study: 100% greywater, 100% potable water (control), a 50/50 mixing of greywater and potable water, and alternating potable and greywater irrigation.

Remarkably, when compared to the control, they discovered that greywater irrigation had no appreciable impact on the dry biomass of plants, including both shoot and root biomass. This implies that greywater irrigation might not have a detrimental effect on production for some crops. Deeming it statistically insignificant, researchers did see a modest tendency of decreased shoot and root biomass in plants that were watered with 100% greywater. These results proceed contrary to some earlier research, which indicated that greywater had a negative impact on plant development. An earlier study [77] on lettuce plants revealed indications of chlorosis within 30 days of greywater irrigation. The disparities in the outcomes emphasize how crucial it is to take crop-specific reactions to greywater irrigation into account.

In a thorough investigation spanning six development cycles, ref. [78] compared the effects of fertilizer solution irrigation, tap water, and greywater on Swiss chard (*Beta vulgaris var. cicla*) and carrot (*Daucus carota*) crops. When compared to tap water irrigation, they discovered that greywater irrigation greatly enhanced plant development and yield for both species. Though it was continuously less than that of plants watered with nutrient solution, the amount of produce from plants irrigated with greywater was higher than that of plants irrigated with tap water. Greywater irrigation boosted the development of Swiss chard from its initial phase to the following growth cycle; however, the plant then declined. The yields of carrots from all treatments including greywater declined gradually over time, which may indicate soil weariness or the buildup of harmful materials. These results show that greywater may be used for small-scale irrigation as a low-grade fertilizer and as a supply of water, especially in nutrient-poor soils wherein sole treatment with tap water may cause extremely poor growth.

Additionally, the [78] study shed light on how crop quality is affected by greywater irrigation. When compared to crops watered with tap water, crops grown under greywater had noticeably larger amounts of macronutrients (N, P, K, Ca, Mg, and S). These values matched those of crops that were watered with fertilizer solution. When compared to tap water irrigation, greywater irrigation also produced crops with greater amounts of micronutrients (Zn, Cu, Mn, Fe, Al, and B). But it also resulted in alarming elevations in sodium (Na) concentrations. The study found that crops with consecutive growth cycles had higher concentrations of Na and metals, especially root vegetables such as carrots. This trend suggests potential long-term risks associated with continuous greywater irrigation. Notably, root crops showed higher accumulation of Na and metals compared to leafy crops, again indicating that crop selection may be an important consideration when using greywater for irrigation.

In contrast to the aforementioned findings, ref. [79] conducted a similar investigation in a greenhouse that compared the effects of different greywaters, which included untreated, treated, and tap water on lettuce (*Lactuca sativa*), carrots (*Daucus carota*), and peppers (*Capsicum annum*). The research revealed no discernible variation in crop dry biomass between plants receiving standard tap water and those watered with different variations in greywater. The outcome was ascribed to the low nutritional content and minimal concentrations of heavy metals in the study's greywater, neither of which inhibited plant development. Regardless of the watering method, every plant developed in a healthy manner and yielded fruit. These results showcase the implication that in comparison to tap water irrigation, greywater irrigation may not always result in higher crop yields, particularly if the greywater contains minimal nutritional value. However, it is important to note that the greywater used in this study had relatively low levels of nitrogen (1.2–6.2 mg/L), phosphorus (0.24–1.21 mg/L), and potassium (0.6–4.4 mg/L), which may not be representative of all greywater sources. In cases where greywater contains higher nutrient levels, it might potentially serve as a low-grade fertilizer and positively impact crop yields.

The nutrient content in greywater can fluctuate daily based on household activities, making it difficult to predict and manage nutrient inputs accurately. Additionally, greywater may not provide nutrients in the optimal ratios required for specific crops, potentially leading to deficiencies or excesses of certain elements. To address these issues, regular soil testing becomes crucial to track nutrient levels and prevent over- or under-fertilization. Different crops have varying nutrient requirements, so irrigation and supplemental fertilization strategies should be tailored to each crop type. Furthermore, continuous greywater irrigation can alter soil pH and nutrient availability over time, necessitating adaptive management strategies. By considering these factors, farmers can develop appropriate nutrient management plans for their greywater-irrigated crops, potentially benefiting from the additional nutrient inputs while mitigating risks associated with nutrient imbalances or excesses. This approach ensures that the use of greywater for irrigation can be optimized for specific crop needs while maintaining long-term soil health and productivity.

7. Case Studies of Successful Greywater Irrigation Projects

In many countries around the globe, greywater agriculture initiatives are gaining popularity as a long-term answer to water preservation. Such initiatives entail the distribution of processed greywater from homes and businesses, a practice that not only lessens the need for potable water but also offers a consistent water supply for gardening and agrarian endeavors. The condition of greywater, the effectiveness of the purification process, the planning and execution of the irrigation, and societal opinion and approval of the utilization of processed greywater are just a few of the many variables that affect the viability of such applications. These initiatives have been effective in tackling the challenge of water shortage while additionally showing the advantages of greywater reuse from a financial and ecological standpoint. In this scenario, it is critical to comprehend the crucial elements that made these initiatives successful as well as the insights that may be applied to similar endeavors down the road.

A study by Turner et al. (2013) [59] investigated the feasibility of greywater irrigation on a large timescale. The research aimed to determine the overall feasibility of greywater irrigation while keeping water reutilization in mind and to investigate any consequences, foreseeable or otherwise. The need for determining the impacts stems from the lack of regulatory oversight for phosphorous loading of soil within Australia where the study took place. The investigation was designed to split four urban areas for irrigation with treated greywater via subsurface drip irrigation with soil samples being retrieved and analyzed for chemical and physical changes along with regular testing of the greywater being produced. The phosphorous levels of the soil and the potential levels accumulated via greywater analysis were also subjected to scrutiny with the entire study taking place over 4 years. Turner et al. (2013) [59] determined that given that the four watered plots cumulatively used less freshwater by a value of 1.6 million liters across four years, the results demonstrate the merits of greywater usage in terms of water conservation. However, phosphorous contamination of the surrounding environment via elevated levels in plots A and C was also observed, but the concern was quickly dispelled once it was shown that plot D, which received no treatment, had environmentally hazardous phosphorus values. But with appropriate handling, plot D may potentially be deemed viable and plot B was found to have similar values and risk of control (non-watered) plots. Turner et al. (2013) [59] further determined that consumers might not be aware of or even be unwilling to recognize the link between how one's home goods affect ground health and greywater conditions. Likewise, the situations concerning plots A and C might have been averted; moreover, plot D could have been adequately handled if present laws and regulations had objectives and provided support regarding the application of phosphates via watering. Awareness campaigns along with a change in local laws and legislation might persuade locals to consciously manage and reduce their ecological cost by being aware of how domestic goods affect the makeup of greywater. It would also help greywater irrigation provide viable results. With greater knowledge and laws, additional families might be able to use greywater in their homes in a manner that produces viable results and averts ecological contamination.

Another article by Yalçinalp et al. (2019) [80] investigated the possibility of utilizing greywater irrigation on green roofs in terms of water reutilization, which has been gaining popularity as a renewable architectural element in urban settings in Turkey. The goal of the investigation is to determine how greywater affects vegetated roof development of flora, coverage, and water usage efficacy. *Sedum sediforme* and *Sedum album*, two types of green roofing vegetation, were used in a potted trial by the authors. Greywater and potable water were employed to hydrate the crops, with various on-site dilutions produced before administration. The investigators monitored plant coverage and both water and soil nutrient levels throughout the 2-year trial. A comprehensive analysis of the research revealed a substantial variation in the roof areas covered by *Sedum* sp. when it was watered or not. Furthermore, using GW as a novel watering technique, it was shown that this acceptable water supply may reduce or perhaps completely replace the use of significant and costly tap water. The usage of greywater also had a more favorable impact on vegetation development than the use of tap water in terms of coverage. In that way, by employing greywater in green roof projects, it could be feasible to produce outcomes that are more advantageous from a financial and environmental standpoint, as well as minimize water use and encourage plant development. Using this methodology would lower green roof projects' watering expenses over time due to continued and widespread use, making them a rather increasingly viable and affordable choice.

The components of different treatments may also have varying effects in terms of greywater treatment as shown in an article investigating a decentralized system for greywater reuse within Chile by Rodríguez et al. (2022) [81]. The experiment involves batch and continuous flow adsorption methodologies being implemented with synthetic greywater as the test subject for purification with a pilot scale purification system being set up within a school located in a remote region. The results indicate that heat and acid-activated charcoal materials were ideal for organic adsorption. Columns prepared with varying layers of sand, zeolite, and heat-activated charcoal were effective at lowering turbidity with close to 100% removal efficiency. However, they were prone to clogging with suspended particulate following roughly 80 min of operation, indicating the need for a cleaning/backwash protocol to be implemented in a large-scale operation. Last but not least, the preliminary purification systems installed in the educational institution demonstrated effectiveness at removing soluble Chemical Oxygen Demand, lowering Total Dissolved Solids, and eliminating turbidity, allowing compliance with the guidelines for water quality for irrigation purposes of sports fields and, in certain instances, decorative cultivation, making it feasible to employ treated greywater for watering vegetation and green spaces in schools. An additional measure that may be suggested from these findings is to determine microbial content within the treated greywater and whether irrigation and aerosolization of the water are safe for public health. These findings support the efficacy of straightforward, inexpensive greywater treatment devices capable of supplying irrigation-worthy water, which are particularly valuable for conserving water in isolated regions with limited water supplies.

Green walls, often referred to as vegetated walls, are increasingly prominent as creative and long-lasting urban landscaping alternatives. Within such "vertical gardens," flora are grown on custom-built supports that are fastened onto construction surfaces or similar elevated areas. They additionally have a pleasing appearance but also several ecological perks including better air quality [82], lessened urban heat island impacts [83–85] and encouragement of fauna and species biodiversity of insects [86].

8. Benefits and Challenges of Vegetated Wall Systems

Vegetated wall systems provide several advantages that go beyond conventional farming techniques, making their incorporation into urban settings an exciting alternative to agricultural activities. The way we envision agricultural space in cities is completely changed by these technologies' remarkable ability to optimize capacity in urban environments. Without vying for limited urban ground resources, vegetated walls provide new possibilities for food production by using vertical surfaces that might otherwise remain barren. In heavily populated metropolitan areas where conventional horizontal agricultural sites are lacking or nonexistent, this vertical method of agriculture can be considered beneficial.

8.1. Benefits

Vegetated wall systems have environmental benefits that far surpass their main use in agriculture and greatly enhance urban sustainability. By employing an array of processes, such structures are essential for controlling building temperatures. Cultivation medium and plant transpiration work together to produce an intrinsic cooling phenomenon in the hottest seasons and serve as extra insulation in the cooler ones [87,88]. It has been demonstrated that this thermal control capacity may lower building energy use between 16.5% for 51% for heating and cooling, respectively, especially in buildings that receive a lot of sunlight [89]. Additionally, the vegetative cover efficiently captures particulate matter and airborne contaminants, functioning as a natural air filtering system via deposition or direct impact [90]. Substantial decreases in metropolitan airborne contaminants have been observed throughout the vicinity of vegetated walls with studies reporting single-pass removal efficiency of species such as *Nephrolepis exaltata* of roughly 80% with regards to PM 2.5–5 and above [91].

Another important advantage of vegetated wall systems is preserving water, especially when combined with greywater irrigation. Because of its vertical design, which enables gravity-assisted circulation of water as well as the possibility of water retention and reuse, these types of structures exhibit exceptional water utilization efficiency. In comparison to conventional horizontal farming techniques, the vertical arrangement allows a cascading stream of water that optimizes absorption while reducing waste, resulting in an irrigation system that is intrinsically more efficient [92]. These walls develop further into environmentally friendly technologies when paired with greywater systems, providing a workable way to recycle water in urban settings. Via physical and biological purification operations, the growing medium in vegetated walls serves as a natural filtering system that may enhance the quality of greywater [92]. Furthermore, it is important to recognize the role that vegetated walls play in promoting urban biodiversity. By providing vertical homes for a variety of insects, birds, and other urban wildlife creatures, these structures contribute to the preservation of biological pathways in urban settings. These networks' ecological significance is further increased by the variety of plant species that may be integrated into them, opening up possibilities for the preservation of regional plant types and the provision of urban ecosystem services including pollination [93].

Arguably, the most attractive features of vegetated wall systems may be the flexibility of these advantages. The advantages grow proportionately from single-building installations to district-wide applications, indicating substantial potential for greater urban change. The all-encompassing advantages of vegetated wall systems make them an essential part of future urban development plans as cities tend to expand and confront more sustainability-related issues.

8.2. Challenges

Vegetated wall system application poses a number of intricate problems that demand critical evaluation and unique remedies. To guarantee system longevity and success, these issues require specialized consideration in the technological, biological, and operational realms.

When putting vegetated wall systems into practice, one of the main technical hurdles is structural compatibility. Growing medium, plants, storage of water, and the structural arrangement alone create heavy extra stresses on facilities. The weights may be too high for existing buildings to be retrofitted directly and are dependent on the choice of plant and system architecture [94]. Retrofitting older structures presents a unique difficulty since structural capacity may be constrained or expensive reinforcing may be needed. Additionally, because of the distinct stress distributions that the vertical orientation produces on building exteriors, waterproofing, thermal expansion, and protective barriers must be carefully considered in order to stop root intrusion and moisture-related degradation of building elements [95].

Another issue in vertical systems, notably those that use greywater irrigation, may make nutrient management more difficult. Nutrient deposition in lower areas and leaching through higher portions might result from the water's vertical movement. With greywater irrigation, salt buildup is especially problematic since dissolved salts can accumulate in the growth media over time and perhaps reach phytotoxic proportions [78]. Sustaining ideal nutrition levels over the vertical profile is difficult and calls for complicated tracking and administration infrastructure, which frequently raises operational complexity and expense. Furthermore, there are major operational issues when it comes to maintenance access. In contrast to conventional horizontal agriculture, vertical systems necessitate specific tools and safety measures to sustain plants at a height. Routine chores like system maintenance, pest control, and trimming are increasingly difficult and perhaps dangerous. Operational expenses can be greatly impacted by the requirement for skilled workers and specialized maintenance equipment. Additionally, because these systems are visible in building exteriors, aesthetic servicing becomes essential, which further complicates the need for routine maintenance. Other technical difficulties arise when integrating with various building types. Residential and commercial water distribution and drainage systems must be synchronized with the irrigation system, which may be needed for complex controllers to avoid spillage or water damage. To avoid moisture-related problems, the vegetated wall's contact with the building ventilation systems needs to be properly controlled. Furthermore, system design must carefully consider the effects on building exterior effectiveness, particularly thermal and moisture mechanics [95].

Since many large-scale installations of green walls are very new, there is still significant uncertainty over their long-term viability and longevity. Servicing expenditures, equipment repair needs, and system lifetime are still issues. The requirement for regular replacement of growth medium, possible structural degradation over time, and development of plant communities all add to ambiguity regarding long-term planning and cost estimates.

8.3. Vegetated Wall Studies Under Greywater Irrigation

The rapid evolution of greywater irrigation techniques has led to an increase in the utilization of such a resource for various irrigation methods. Therefore, it comes as no surprise that greywater irrigation can be effectively utilized for green walls as well and scientists are constantly looking for methods of implementation and purification. Some of these methods and current implementations are discussed below.

A study by Chung et al. (2021) [96] explores the application of greywater to support plant growth on green facades. The investigation found that following 18 weeks of treatment, neither greywater irrigation methods nor greywater combined with clean water caused a substantial or detrimental shift in the substrate's attributes, including pH. When juxtaposed with sanitary water cultivation, neither of the two greywater procedures for the six climber species of plants (*A. quinate*, *G. semperivirens*, *J. azoricum*, *P. pandorana*, *T. jasminoides*, and *Vitis*) under study substantially decreased plant development with regard to the plant matter, root/shoot distribution and surface area of leaves, gaseous conversion ratios in addition to photosynthetic and transpiration ratios, or the consumption of water. The findings showed that indirect green façades in densely populated areas may be designed more sustainably by minimizing the usage of clean water while securely irrigating climbing vegetation with dwelling greywater. It is further determined that the early stages of plant development, i.e., the establishment phase, may be the most crucial in determining the success of growth.

Another study with multiple media implementations was conducted by Pradhan et al. (2019) [21] and investigated the greywater treatment of ornamental plants and media within a green wall system. The plant species involved in the study are *R. brittoniana*, *A. dentata*, *T. domingensis*, *A. wilkesiana*, *K. glauca*, and *P. grandiflora* with media types consisting of perlite, coco coir, SCG, date stone, LECA, and sand. The objective of the study was mainly to determine the efficacy of decorative plants and supporting substrates that may be included in urban landscaping in removing greywater contaminants. They examined the remediation capabilities and in-depth extraction processes for nutrients and biological material from greywater. Sand, coco coir, and other large contact dimensions, and low-diameter substrates had the best elimination efficacy, which was mostly attributed to degradation by microbes. It was shown that media choice had a noticeably bigger influence on treatment effectiveness than vegetation choice, enabling flexibility in plant choices for environmental and decorative purposes. However, vegetation helped with treatment, especially by improving nitrification and phosphate removal. Even hydrophobic and aqueous chemicals were successfully removed from organics by the mechanism, and over a period of time, all contaminants were treated more efficiently. The study successfully highlights the various changes greywater can induce and the possible pollutants that can be removed from within it by implementing the right type of media for growth.

The climate within which a green wall is built is a crucial part of its growth and health and too high or low temperatures may easily damage seedlings and even fully mature plants. A pilot scale study by Karima et al. (2021) [97] investigated exactly such phenomena and involved greywater application on green facades within a Mediterranean environment.

The key point was investigated by placing green facades in north, east, and west orientations to determine the quantity of greywater that may be required due to varying sunlight and wind conditions. The species investigated were a multitude of native and non-native climbers and groundcovers along with a growth media known as gingin loam and a mix of native media. The result concluded with irrigation across the various orientations being successful along with times of the year when a cooler temperature prevails such as May–September in Perth where the experiment was conducted, allowing a lowered requirement for volume of greywater irrigation. This is indicated by the lowered evapotranspiration observed in both the deciduous and non-deciduous species investigated. By choosing the right soil and plant varieties, it was shown that greywater-treated green façades might thrive in Perth's Mediterranean weather, which features scorching summers and rainy winters. The study also showed that greater watering frequencies enhanced the amount of water used by plants as well as the amount of outflow, providing chances for recycled effluent. Furthermore, the study states that the required outflow quantities and other aspects of design unrelated to greywater treatment ought to be taken into consideration when deciding whether to use deciduous or non-deciduous vegetation.

9. Conclusions

Water scarcity and shortage is a global concern as freshwater resources continue to decline due to human actions. To ensure our survival, it is crucial to explore alternative approaches and conservation techniques. One such alternative is the utilization of greywater, which refers to wastewater originating from residential sources like sinks, washing machines, and bathroom fixtures, excluding toilet water. Greywater is multipurpose (used in toilet flushing, irrigation, and green walls) and promises a sustainable approach to water reuse. Greywater varies in its characteristics (pH, conductivity, nutrients, biological factors, physiochemical factors, and salinity) and sources, making it complex but interesting to learn. The reuse of greywater has benefits (cost-effectiveness, plant growth) and challenges (system management, toxicity, and water hydrophobicity). Scientists are able to study all these factors and design treatment systems and plans helpful to the environment.

In summary, the studies reviewed on effective greywater irrigation schemes show the potential of employing processed greywater for agriculture. These initiatives have demonstrated that treated greywater may be a sensible substitute water supply that can lessen the need for freshwater supplies and offer a wide range of financial and ecological advantages. The effective execution of these initiatives has needed a deep review of aspects including remediation techniques, preservation, transmission, vegetation choices, and security precautions. Already, such initiatives have shown how greywater may be utilized to irrigate a wide variety of vegetation, particularly agricultural produce and rooftop gardens. It is crucial to remember that there are obstacles that must be overcome for greywater irrigation schemes to be implemented successfully. These obstacles include legislative and social restrictions, technological limits, and prospective health hazards. In order to stop the spread of viruses and other pollutants to people and the natural world, it is essential to guarantee that the proper treatment procedures and precautionary steps are in operation. The research articles on effective greywater irrigation schemes illustrate the need for thorough preparation and execution to guarantee the security and effectiveness of these operations and offer insightful information on the possibilities of greywater as a renewable source of water. Ultimately, such accomplished greywater irrigation initiatives display the possibilities for the secure and productive utilization of greywater and can therefore act as reference templates for other institutions interested in carrying out initiatives of this nature.

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