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From drainage to resource: a practice approach to reuse greywater for household irrigation purposes

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ABSTRACT

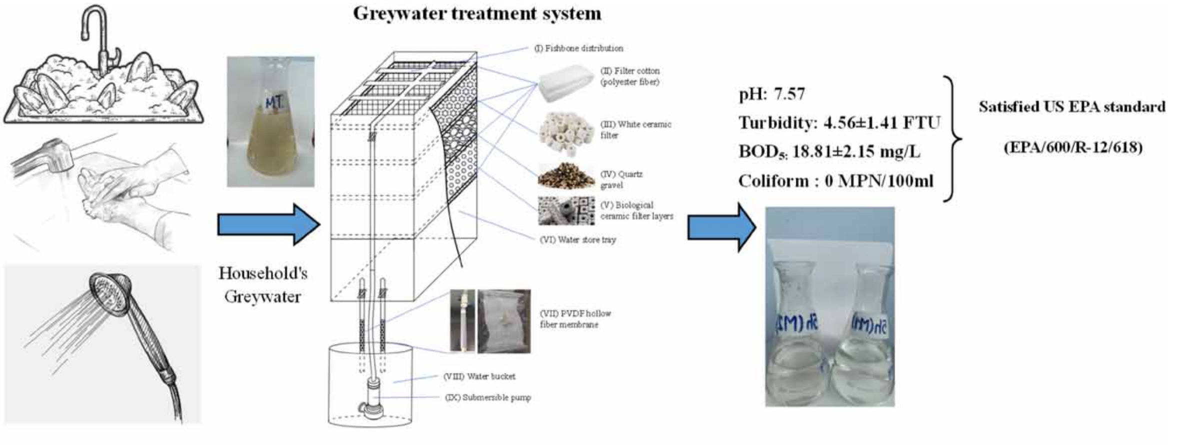
The United Nations indicates that available freshwater resources will decrease significantly due to pollution growth and urbanization; two-thirds of the world's population may face water shortages by 2030. Extended use of greywater is an alternative option for reducing potable water consumption in urban areas. Recently, the reuse of treated greywater for home gardens, peri-urban agriculture, and landscaping has become a widespread concern in many developing countries. This paper presents a study on a low-cost system that can perform greywater treatment for household use. This treatment system employed physical filtration by ceramic filters, quartz gravel, hollow fiber membrane, and UV disinfection. Three greywater samples collected from the kitchen, washing basins, and bathroom were investigated. The operation process determines the system's effectiveness by considering turbidity, coliform, Biochemical Oxygen Demand (BOD_5), and Chemical Oxygen Demand (COD) concentration of the inlet and outlet water. As a result, high removal efficiency (i.e., $>$60%) could be obtained for each investigated parameter. Results also showed that grey water generated from washing basins has the highest potential for reuse since the water quality after treatment satisfies the water reuse standards for household irrigation. The findings encourage further exploration and implementation of greywater reuse practices.

Key words: greywater, household irrigation, SDG6, UV disinfection, water reuse

HIGHLIGHTS

- A greywater treatment system with six filter layers and a PVDF hollow fiber membrane was investigated.
- The system's performance was assessed by measuring the pH, turbidity, BOD_5, COD, and coliform concentration.
- UV disinfection made washing basin greywater suitable for garden irrigation, meeting international standards.
- An efficient and cost-effective system for greywater reuse in Southeast Asian households.

GRAPHICAL ABSTRACT



INTRODUCTION

Agricultural irrigation accounts for about 70% of global freshwater withdrawals. In some countries, landscape irrigation during the summer can consume up to 40% of the total water consumption in a single residence (Al-Ismaili *et al.* 2017). However, the United Nations indicates that available freshwater resources will decrease significantly due to increased pollution and urbanization, leading to two-thirds of the world's population facing water shortages by 2030 (UN 2016). Water security is becoming a major challenge for many countries, especially developing ones (AbuEltayef *et al.* 2023; Ta & Promchan 2024). Many of the world's poorest people still live in areas without clean water or adequate sanitation. Additionally, more water is required to produce enough food and energy to meet the increasing demands of the growing population. Thus, waste/greywater reuse holds significant importance in developing countries, offering a strategic solution to address water scarcity challenges. As these nations grapple with population growth, urbanization, and climate change, reusing treated wastewater emerges as a crucial alternative water source. The economic efficiency of wastewater reuse becomes evident, providing a cost-effective solution to water supply issues, particularly in resource-constrained settings (Liao *et al.* 2021). Developing countries can reduce pressure on freshwater resources and enhance nutrient recovery by employing treated wastewater for agricultural irrigation, promoting sustainable farming practices (Swana *et al.* 2020). Additionally, the environmental benefits are substantial, as wastewater reuse helps protect ecosystems, mitigates pollution, and contributes to climate resilience (Landa-Cansigno *et al.* 2020).

Recently, the reuse of greywater for household irrigation has attracted more attention. Greywater is the non-toilet portion of wastewater, primarily generated from bathrooms, washing basins, laundry, and kitchens. Greywater is a potentially reusable water resource for household lawn and garden irrigation since it has a low macronutrient content (Misra *et al.* 2010). Several technologies have emerged to recycle and reuse grey water. Different physical and chemical treatments can be used depending on the greywater sources' qualities. Filtration, for instance, uses a variety of systems, including cartridge filters, coarse filtration, sand filtration, and ultra-filtration membranes, to remove suspended particles, certain organic materials, and pathogens (Li *et al.* 2009). Chemical treatments such as photocatalytic oxidation and magnetic ion exchange resins have also been successfully applied to greywater reuse (Pidou *et al.* 2009). Biological technologies, including rotating biological contactors (Friedler & Hadari 2006), membrane bioreactors (Lamine *et al.* 2012), and sequencing batch reactors (Scheumann & Kraume 2009), are also widely used for treating grey water. Li *et al.* (2009) state that the most economical and feasible technique for recycling greywater combines an aerobic biological process with physical filtration and disinfection. However, due to the limitations in monitoring and maintenance, greywater reuse is still on a small scale in developing countries (Radingoana *et al.* 2020). Furthermore, the type of greywater for reuse is also important, affecting the treatment system's feasibility and practical application. Therefore, different types of greywater samples should be considered and investigated to determine the appropriate solution.

Currently, water reuse standards vary significantly among countries worldwide, reflecting diverse regulatory frameworks, technological capabilities, and local water scarcity challenges. Some developed countries, such as Singapore, Australia, and Europe, have developed stringent guidelines and standards to promote water reuse in agriculture and industrial applications. In contrast, many developing countries from Africa, South America, and parts of Asia lack national regulations specifically addressing household water reuse (Goyal & Kumar 2021; Kanchanapiya & Tantisattayakul 2022; Shrestha *et al.* 2023; Widianingtias *et al.* 2023). Consequently, the countries often refer to international standards or regulations from developed countries such as ISO 16075 (Guidelines for treated wastewater use for irrigation projects, 2015) (ISO 2015), U.S. EPA 600/R-12/618 (Guidelines for water reuse, 2012) (USEPA 2012), WHO (Guidelines for the safe use of wastewater (excreta and greywater), 2006). Some common parameters included in the water quality standards for reuse water in irrigation are coliform ($\leq$100 CFU/100 mL (ISO 2015); $\leq$10,000 CFU/100 mL (WHO 2006)), turbidity ($\leq$2 NTU (USEPA 2012); $\leq$5 (ISO 2015)), suspended solid ($\leq$30 mg/L (USEPA 2012); $\leq$50 mg/L (ISO 2015)), Biochemical Oxygen Demand (BOD) ($\leq$10 mg/L (ISO 2015); $\leq$30 mg/L (USEPA 2012)), and pH (6.0–9.0) (USEPA 2012).

Under the above circumstances, the major aim of this study is to design and investigate a lab-scale system for greywater treatment to improve household water reuse and conservation patterns. This treatment system employed physical filtration by ceramic filters and quartz gravel as pre-treatment of membrane filtration with a hollow fiber membrane. UV lights are also used for advanced disinfection to remove pathogens and ensure water quality for reuse. Three greywater sources collected from the kitchen, washing basins, and bathroom were used to simulate practical application during the study. The operation process determines the system's effectiveness by considering turbidity, coliform, BOD_5, and Chemical Oxygen Demand (COD) concentration of the inlet and outlet water.

In contrast to some existing methods discussed in the literature, which predominantly rely on biological processes or chemical treatments, our study approach integrates physical filtration, membrane filtration, and advanced disinfection techniques to ensure the highest quality of treated greywater. This study uses ceramic filters and quartz gravel as pretreatment for membrane filtration, employing a hollow fiber membrane. This combination efficiently removes suspended particles and organic materials, establishing a pre-treatment phase before the membrane filtration. The use of ceramic filters and quartz gravel, renowned for their durability and effectiveness, enhances the longevity and reliability of the treatment system (Loh *et al.* 2021). Furthermore, integrating UV lights for advanced disinfection is a breakthrough in eliminating pathogens from greywater. This method adds an extra layer of protection and reduces reliance on chemical disinfectants, enhancing environmental friendliness (Winward *et al.* 2008). The multi-step approach, combining physical filtration, membrane filtration, and advanced disinfection, aims to overcome limitations in existing greywater reuse systems. Thus, this study balances effectiveness, economic feasibility, and environmental sustainability.

MATERIALS AND METHODS

Greywater sources

Three types of greywater samples from households' kitchens, washing basins, and bathrooms in Ho Chi Minh City (HCMC) were collected for experiments in lab-scale treatment. Samples were collected during morning and afternoon sessions in March and April 2022, following the water sampling guidelines (ISO 5667/10:1992). Five households in District 7 of HCMC, specifically residential houses without commercial activities, were selected for sample collection. Each household has a population ranging from 2 to 4 individuals, with the majority engaging in cooking activities within their homes. The three types of greywater samples were collected separately at each household. Subsequently, each type of greywater from the five households was combined to obtain 60 L of each greywater type. This step helps to obtain the representative water samples. The water samples were stored in pre-cleaned plastic buckets, transported to the laboratory, and kept at 5 °C before experiments. The water samples were characterized by physicochemical (i.e., pH, turbidity, BOD_5, and COD) and microbiological (Coliform) parameters. In addition, water from an internal canal was collected for testing in the initial stages of treatment systems after fabrication and installation. This testing stage helped to determine the optimum conditions of the systems before operating with the greywater samples.

Description of the treatment system

Two grey water treatment systems were fabricated from plastic material with a maximum capacity of 25 L. Each system included six filter layers, as shown in Figure 1.

Filter cotton layers were made of polyester fiber to remove suspended solid particles and increase water contact time with other filter layers. The quartz gravel layer with gravels of 2–4 mm assists in removing fine solid particles. The white ceramic and biological ceramic filter layers can help to absorb metals and remove organic materials,

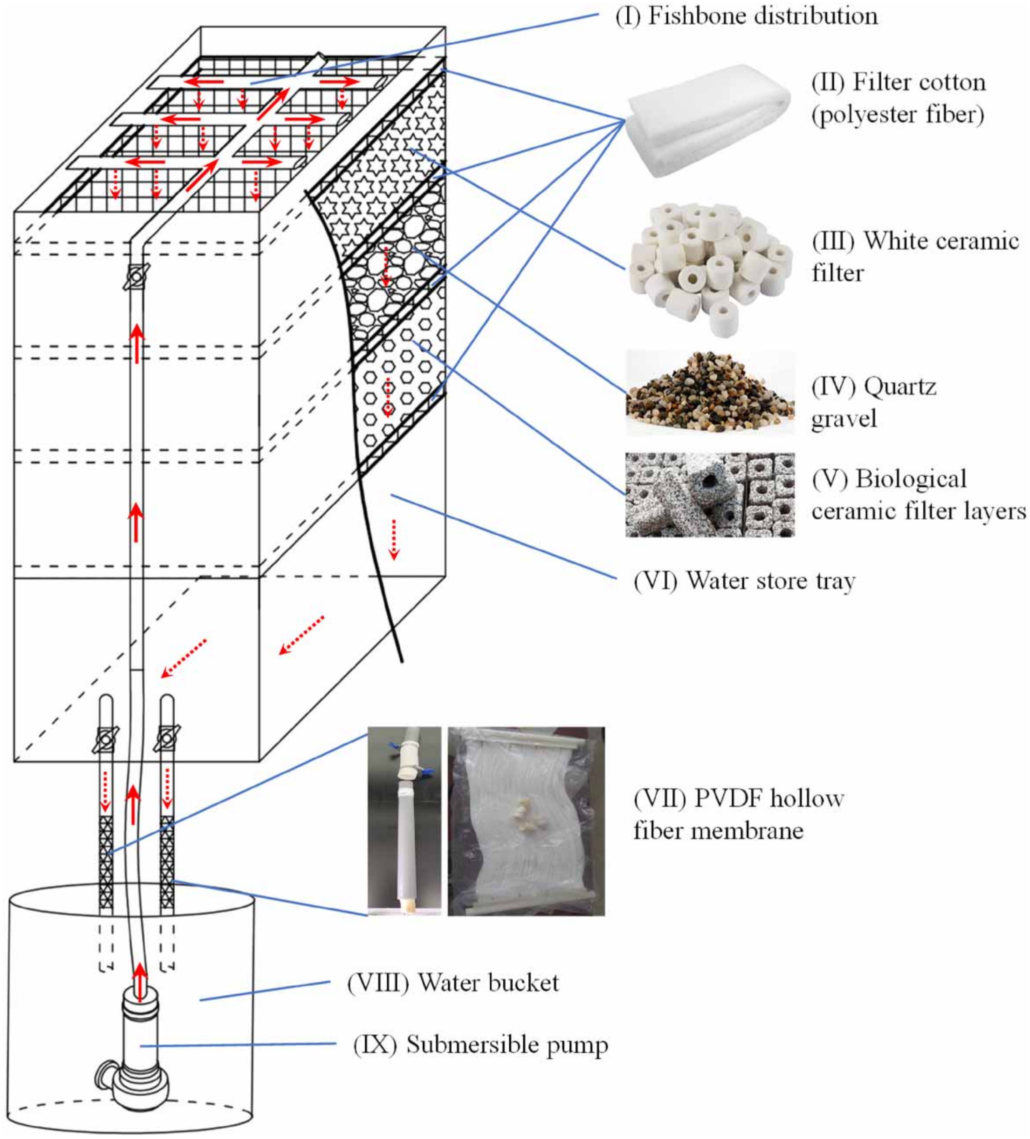


Figure 1 | A lab-scale greywater treatment system.

ammonium, and nitrate compounds in water samples. A polyvinylidene difluoride (PVDF) hollow fiber membrane with a pore size of 0.1 μm was connected with the effluent of the biological ceramic filter layer as the last treatment step.

Experimental design and operation

Filtration without UV disinfection

In order to optimize the performance of the filtration system, preliminary experiments were conducted to assess the impact of varying water retention times and flux rates. Retention times were systematically altered from 1 to 10 h, while flux rates were adjusted across a range of values. Based on the results of these preliminary experiments, a water retention time of 5 h and a flux rate of 208 L/h/m^2 were identified as the optimal conditions for efficient pollutant removal. Therefore, the parameters were applied to the following experiments in this study.

The duplicate treatment systems were operated separately with three greywater samples (i.e., households' kitchens, washing basins, and bathrooms). The raw water samples were stored in a 25-L plastic bucket (VIII – Figure 1). A submersible pump (IX) installed inside the bucket conveyed the grey water into the filtration systems through a fishbone distribution channel (I). This helps to ensure water can be ubiquitously separated on the surface of filtration layers. Grey water flowed under the effects of gravity through different filter media (II, III, IV, V). Permeated water was stored in the last tray (VI) before filtered through the PVDF hollow fiber membrane (VII).

The permeated water was recirculated into the treatment systems in 5 h to increase the treatment efficiency of the system. The flux rate of the system was controlled at 208 L $h^{-1}.m^{-2}$. Permeate water samples were collected every hour for analysis of pH and turbidity. After 5 h of operation, the samples were collected for pH and turbidity, BOD_5, COD, and coliform analysis.

The physical treatment performance characterized by removing turbidity, BOD_5, COD, and coliform was defined, which helped determine the appropriate greywater type for potential reuse. The chosen greywater type was then used for the following experiments with UV disinfection to enhance the treatment efficiency and ensure water quality safety in microbiology.

Filtration system with UV disinfection

The UV disinfection step followed the experiment as described in 'Filtration system without UV disinfection'. Low-pressure mercury UV light (VIPSUN, China) was installed in the water store tray (VI) of the treatment system (Figure 1). This UV lamp works at a capacity of 13W and emits UV radiation at 254 nm. These characteristics provided a UV radiation intensity of 40 mW s/cm^2 applied to the liquid medium. Two parallel filtration systems (i.e., with and without UV disinfection) were operated to examine the removal percentage of coliform bacteria in the greywater. Other operation conditions of the filtration systems were maintained with the experiments in section 'Filtration system without UV disinfection'.

Analytical methods

Physicochemical and microbiological parameters were performed per standard water and wastewater methods. pH was frequently measured by pH testers (i.e., model HI98107, Hanna Instruments, Romania). The potassium dichromate method was applied to analyze COD concentration. The COD reagent vials at low range (HI93754A-25 for low COD range of 0–150 mg/L, Hanna Instruments, Romania) were mixed with water samples and digested by a COD heating reactor (HI839800-02, Hanna Instruments, Romania) at predefined temperature settings of 150 °C. Then, the COD Benchtop Photometer (HI83314-02, Hanna Instruments, Romania), supplied with a 16 mm cuvette adapter that accepts digestion vials, was used to measure COD concentration based on the absorbance measurement method at the wavelength of 610 nm. The BOD_5 analysis followed the ISO 5815-1:2019 standard. The samples' initial dissolved oxygen (DO) concentration was measured using a laboratory DO meter (Model HI5421-02, Hanna Instruments, Romania). Subsequently, 20 mL of the samples were diluted with buffered dilution water and transferred to a 300-mL incubation bottle. The prepared sample was then incubated for 5 days at a controlled temperature of 20 °C. After incubation, the final DO concentration was measured, enabling the calculation of BOD_5. Total coliform analysis was conducted using 3M™ Petrifilm™ E. coli/Coliform Count Plate (3M, 6404). 1 mL of the sample was placed using a pipette onto the center of the bottom film. Subsequently, the top film was gently rolled down onto the sample to prevent pushing the sample off the film and to avoid entrapping air bubbles. The plates were then incubated in an oven at 35 °C for 24 h. Total coliform was counted using an optical microscope. The turbidity of water samples was measured using a turbidity meter (HI93703C Hanna). COD, BOD_5, total coliform, and turbidity measurements were conducted in both influent and effluent analyses, accounting for the entire filtration process.

Data analysis

The data were analyzed through Pairwise post-tests using the paired *t*-test to compare RE between the different greywater samples and treatment systems with and without UV disinfection. Statistical analyses were conducted using Minitab Version 17, with a *p*-value threshold 0.05.

RESULTS AND DISCUSSION

Raw water sample characterization

The characteristics of the greywater samples obtained by measurement are shown in Table 1. High concentrations of organic matter and pathogens were observed in all greywater samples. These results are in line with previous studies. Generally, the quality and quantity of greywater produced in houses can vary significantly depending on the household size and the occupants' habits. In smaller houses, greywater tends to exhibit greater fluctuations in both quantity and quality (Fountoulakis *et al.* 2016).

As shown in Table 1, turbidity, BOD_5, and coliform concentration of greywater samples from the household kitchens are significantly higher than samples from the washing basins and bathrooms ($p < 0.05$, paired *t*-test).

Table 1 | Characteristics of greywater (GW) in the studied households and canal water in comparison with greywater reported by previous studies

		Mean value (this study)				
Parameters	**Units**	**Kitchen sink GW**	**Washing basins GW**	**Bathroom GW**	**Internal canal water**	**Previous studies[a] (min–max)**
pH	–	6.13	7.30	6.90	7.60	6.4–10.0
Turbidity	FTU	221.67 ± 1.52	33.14 ± 0.48	43.97 ± 0.82	38.2 ± 0.27	37–444
BOD_5	mg/L	196.50 ± 2.18	150.50 ± 1.68	168.5 ± 3.33	42.83 ± 0.14	56–188
COD	mg/L	277 ± 11.82	332 ± 9.17	274 ± 1.32	66.3 ± 0.58	26–645
Coliform	MPN/100 mL	10.8×10^8	35×10^6	63×10^5	6.2×10^4	$0\text{–}3.4 \times 10^5$

[a] Bani-Melhem *et al.* (2015); Fountoulakis *et al.* (2016); Oteng-Peprah *et al.* (2018).

The high concentration of contaminants in kitchen greywater is understandable due to the remaining organics (meat and vegetables) and inorganics (soils and sand) from the cooking process. This makes greywater from the kitchen highly biodegradable, with a BOD_5/COD ratio of 0.7. The COD value of greywater from washing basins was much higher than the other types. This can be explained by using a high number of surfactants from soaps and personal care products with a low volume of water in washing basins. The low COD concentration of greywater from the bathroom results from dilution caused by the high volume of water used during showers. For canal water, BOD_5, COD, and coliform concentrations are much lower than all greywater samples since the canal serves as stormwater storage.

Performance of a greywater treatment system

Changes in pH

After the treatment, the pH of permeate waters did not change much compared to raw greywater samples. This is because the treatment process was mainly physical filtration without using any chemical or biological processes. For greywater from washing basins, the pH of their permeate water varied in a range of 7.3–7.8, and it was attained to 7.4 after 5 h of operation. The pH of permeated water from bathroom greywater increased from 6.9 (influent) to 7.4 (effluent). Water samples from the kitchen had the lowest pH compared to other greywater types. This may be due to the degradation of organic matter in the kitchen greywater samples. After 5 h of filtration, the pH of the permeate water from the kitchen increased from 6.13 to 6.35. The treated water is in the neutral range (7.7–7.9) for the canal water sample, similar to its influent. Overall, the pH of all treated greywater greywaters from this study is in the same range as other studies using the same treatment techniques (Santos *et al.* 2012; Samayamanthula *et al.* 2019; Tusiime *et al.* 2022). Compared to current guidelines and standards for wastewater reuse in agriculture (Jeong *et al.* 2016), pH-treated waters from the treatment systems can be used for all irrigation purposes.

Removal of turbidity

The changes in turbidity during 5 h of operation in the filtration process are shown in Figure 2. In the first hour, the turbidity decreased rapidly due to the effective filtration of filter media. After 5 h of the operation, turbidities in all greywater samples decreased significantly, corresponding to more than 80% removal percentage. The turbidity of permeate water from the washing basins (3.9 NTU) and bathrooms (8.8 NTU) meets the required standards and guidelines for use in agriculture and gardening (Jeong *et al.* 2016). The final turbidity for treated water from the kitchen was much higher than the other at 27.7 NTU. However, this can still be used for garden irrigation (excluding food crops) (ISO 2015). For canal water, the turbidity of filtered water was reduced to 3.41 NTU, which is 91% lower than its influent. According to most standards and guidelines, treated canal water's turbidity can be used for all irrigation purposes, including food crops (Jeong *et al.* 2016).

In comparison with other research, the removal of turbidity found in this current study is lower than the study by Tusiime *et al.* (2022) (i.e., 92–95%) but much higher than the study by Al-Ismaili *et al.* (2017) (i.e., 40%). This can be explained by the difference in using filtration materials and retention times of the treatment systems in studies. This study utilizes large and medium sizes of filter materials combined with a hollow fiber membrane (Figure 1). The study by Tusiime *et al.* (2022) used thick layers of fine sand (0.4–0.8 mm), sand (0.8 – 2 mm), and gravel (10–20 mm). The hydraulic retention times in their study ranged from 12 to 36 h, much higher than

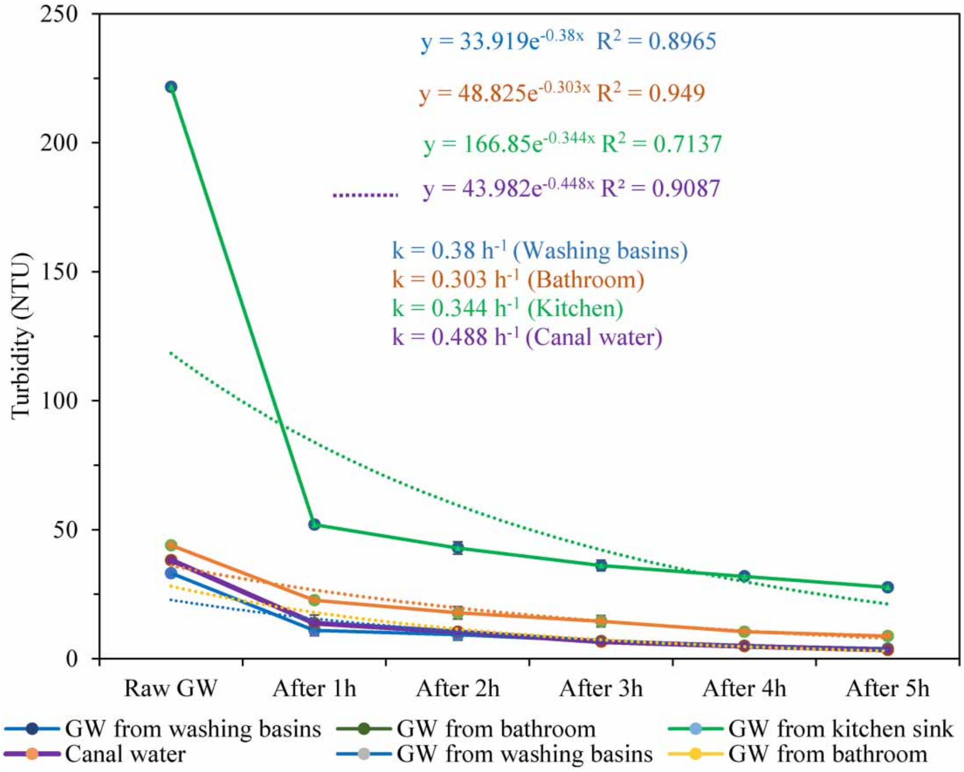


Figure 2 | Change of turbidity in different greywater samples during 5-h operation in the lab-scaled treatment system.

the 5 h in this current study. Thin layers of fine sand (0.2 mm), gravel (6 mm), and big stone were applied in the study by Al-Ismaili *et al.* (2017). This indicates that increased media size deteriorates turbidity removals of greywaters. Similar results were reported by Singh *et al.* (2021) and Xu *et al.* (2020).

Figure 2 also depicts the turbidity removal of greywater samples during operation time in exponential function ($C = C_0 \times e^{-kt}$). The speed of turbidity removal is presented as the k value in the equation, while C and C_0 are effluents and influent turbidity, and t is filtration time. In comparing the three greywaters, treated water from the washing basins achieved the highest k value (0.38), corresponding with the highest removal speed and efficiency.

Removal of BOD_5

The BOD_5 removal efficiency (RE) for each greywater type is shown in Figure 3. After 5 h of filtration and recirculation, the RE in the case of the washing basins (87%) and kitchen sinks (80%) was not much different. However, due to the high BOD_5 concentration of influent from the kitchen, its effluent BOD_5 value (39.75 mg/L) is much higher than that of the washing basins (19.75 mg/L).

The RE of BOD_5 (63%) for water from the bathroom was much lower than that of others. BOD_5 concentration of water output in the bathroom case (69.25 mg/L) and the kitchen sink (39.75) could not be used for irrigation purposes following international standards and guidelines (Jeong *et al.* 2016). However, according to Vietnam's national standard for treated wastewater used for irrigation (i.e., TCVN 12180-2:2017), the water output obtained from the bathroom meets the standard for industrial crops. In the case of washing basins, the treated water achieves the required standard and guidelines for use in garden irrigation (including food crops). The average BOD_5 concentration after the filtration achieved 12.17 mg/L for canal water, which can be used for all irrigation purposes (Jeong *et al.* 2016).

For BOD_5 removal, the efficiency obtained in this current study was lower than that found in the study reported by Niwagaba *et al.* (2014) and Tusiime *et al.* (2022). The observed effects can be attributed to the differences in water retention times across the various filtration systems. This study recirculated greywater in 5 h, while their studies were from 12 to 36 h. This indicated that BOD_5 removal increased with an increase in the retention time of greywater in the filtrations. Niwagaba *et al.* (2014) also revealed that retention time significantly

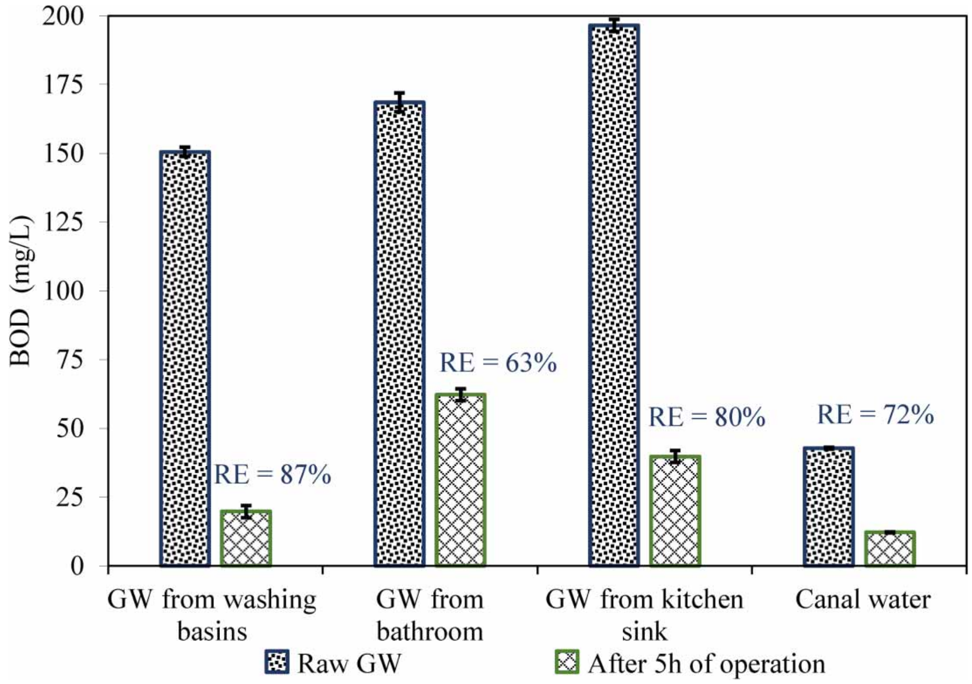


Figure 3 | BOD_5 concentrations of different greywater and canal water after 5 h of filtration.

contributes to BOD_5 reduction. On the other hand, BOD_5 removal found in this work was comparable with other studies of Abdel-Shafy *et al.* (2014), Al-Ismaili *et al.* (2017), and Katukiza *et al.* (2014).

Removal of COD

The COD concentrations of water output are shown in Figure 4. After 5 h of operation, the filtration systems removed 62–77% of COD in greywater samples. Greywater from the kitchen achieved the highest RE with a final COD concentration of 63 mg/L. This is because the main COD of the greywater kitchen was contributed by biodegradation matters such as meat and vegetable particles. Thus, the filtration processes can easily remove these materials. The low RE of COD for washing basins and bathrooms is due to the high concentration

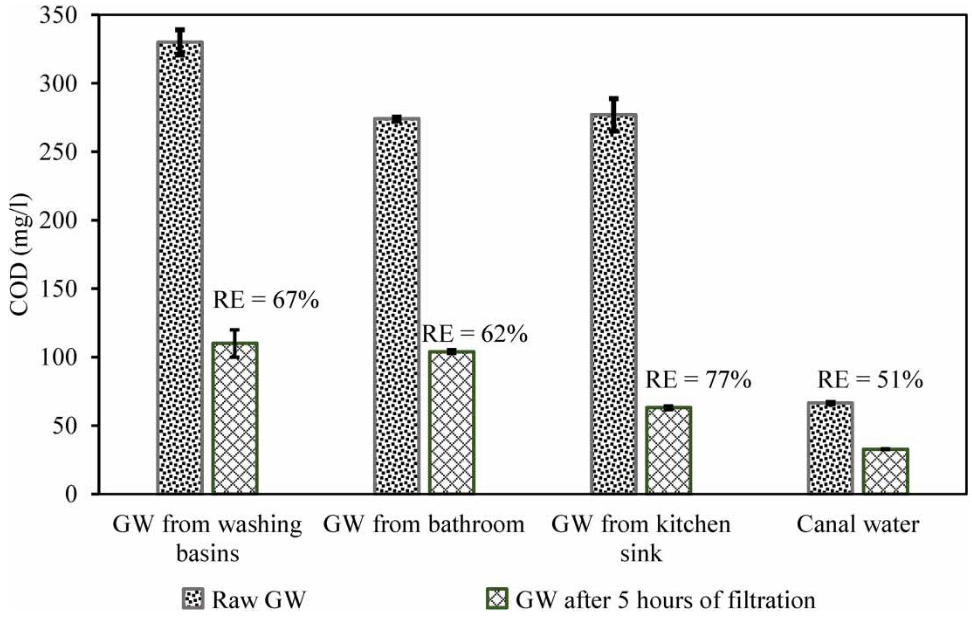


Figure 4 | COD concentrations of different greywater and canal water after 5 h of filtration.

of surfactants in their greywater, which is rarely removed by physical filtration. Those reasons are also explained by the lower RE of COD in comparison with BOD_5 for most of the greywater samples and canal water samples in this study. Few international standards and guidelines for wastewater reuse in agriculture mention COD concentration (Jeong *et al.* 2016). According to guidelines from Israel (SWIM-SM 2013) and Italy (Angelakis & Durham 2008), treated water in the case of kitchen and canal water can be used for irrigation in agriculture.

Other studies using filtration techniques also showed comparable results (Al Jahmani *et al.* 2021; Singh *et al.* 2021). Generally, the filtration treatment effectively reduces organic matter, especially for BOD. The BOD_5/COD ratio also verifies this increase in all three greywater samples after treatment, indicating that BOD is more affected by the filtration process than COD. Similar findings were reported by Santos *et al.* (2012).

Removal of coliform

Coliform is an important parameter to determine whether the treated greywater can be reused for irrigation. As shown in Figure 5, the removal efficiencies of coliform by the filtration processes were still low. Coliform remained at high levels in all the cases. The removal of coliform in this current study was lower than that found by Dalahmeh *et al.* (2014) and (Tusiime *et al.* 2022). This may be due to the lower retention time of greywater in this study (5 h) compared to their studies (12–36 h). Shaikh & Ahammed (2022) also demonstrated that removing organic matter, nutrients, and microbiological parameters decreased at a short retention time of filtration systems.

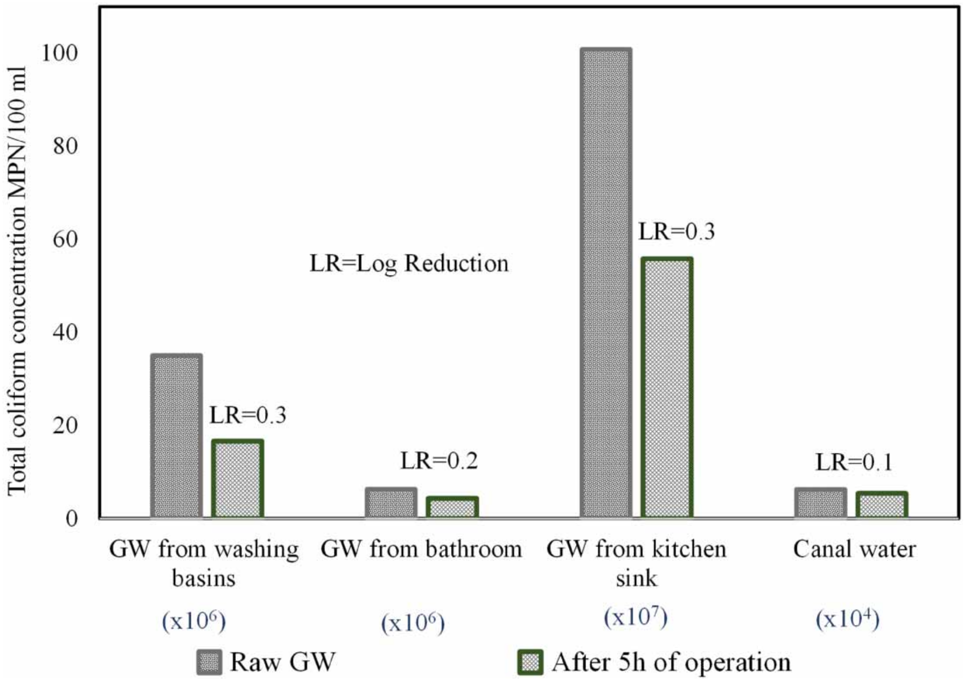


Figure 5 | Total coliform found in different greywater after 5 h of filtration processes.

Although high RE of coliform was reported in the studies by Dalahmeh *et al.* (2014) and (Tusiime *et al.* 2022), the coliform of treated water did not satisfy the current standards and guidelines (Jeong *et al.* 2016), which is similar to the situation observed in this study. Thus, it is important to improve the removal of coliform by further treatment like disinfection to meet the standards for water reuse.

UV disinfection

After filtration, the treated water from washing basins has achieved the highest RE for most parameters, such as turbidity, BOD_5, and COD. The treated water meets the standards outlined in ISO 16075-1:2020 and US EPA EPA/600/R-12/618 for water reuse in irrigation, except for total coliform. Therefore, the water collected from washing basins underwent investigation in this UV disinfection experiment to improve the removal of coliform in the greywater. After 5 h of the treatment process, the water characteristics and RE of pollutants are presented in Table 2. Regarding organic matters, the removal efficiencies were not significantly different ($p < 0.05$, paired

Table 2 | Water characteristics and removal efficiency of pollutants from washing basins with and without UV disinfection as compared to current standards for water reuse in irrigation

	Without UV		**With UV**		**Current standard**	
Parameters	**Mean value**	**RE (%)**	**Mean value**	**RE (%)**	**US EPA EPA/600/R-12/618**[a]	**TCVN 12180-2:2017, ISO 16075**[b]
pH	7.57	–	7.60	–	6.0–9.0	–
Turbidity (FTU)	4.56 ± 1.41	86	5.63 ± 1.93	83	–	–
BOD_5 (mg/L)	18.81 ± 2.15	88	19.57 ± 2.31	87	≤ 30	≤ 20
COD (mg/L)	112.88 ± 3.95	66	116.2 ± 4.05	65	–	–
Coliform (MPN/100 mL)	22.10×10^6	63	0	100	≤ 200	$\leq 1,000$

[a] Suggested guidelines for water reuse in restricted urban areas (USEPA 2012).
[b] Suggested guidelines for water reuse in restricted urban areas (STAMEQ 2017).

t-test) in the case of with and without UV. However, significant changes were found for coliform when UV light was employed. In the experiment with UV disinfection, no coliform was found in the treated greywater (RE = 100%), as shown in Figure 6(c). The same results were reported in previous studies by Do Couto *et al.* (2015) and Friedler & Gilboa (2010) when using UV radiation for greywater disinfection. It was reported that the health risks when reusing greywater properly disinfected with UV radiation are minimized.

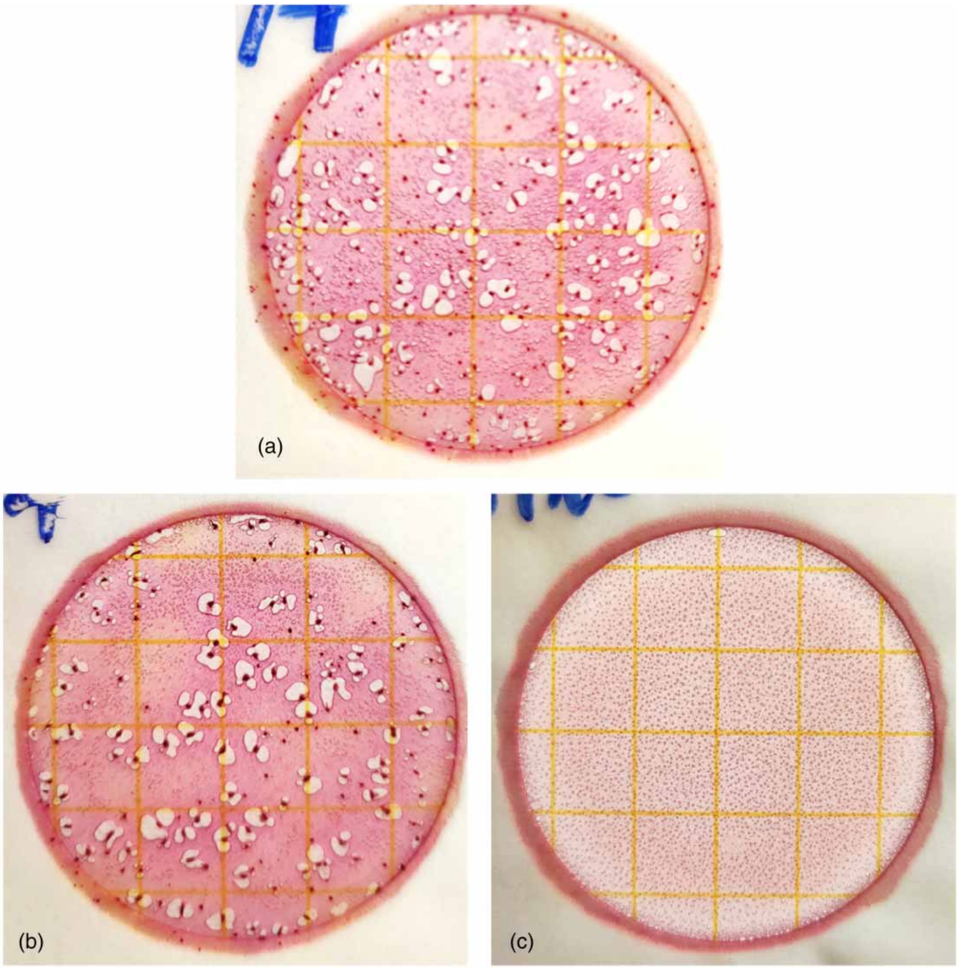


Figure 6 | Formation removal in the case of washing basin water samples: (a) before treatment; (b) treatment without UV; and (c) treatment with UV.

Table 2 also presents characteristics of the treated greywater from washing basins compared with the United States Environmental Protection Agency (USEPA 2012) and Vietnam standards (STAMEQ 2017) for water reuse. The treated greywater with UV disinfection satisfied the allowable limits for reuse in non-potable applications in municipal systems where public access is physically controlled or restricted.

CONCLUSIONS

In conclusion, the study evaluated a lab-scale greywater treatment system consisting of six filter layers and a PVDF hollow fiber membrane. The system effectively reduced turbidity, BOD_5, and COD in various greywater sources. The washing basin's greywater exhibited the best treatment performance, meeting irrigation standards. The addition of UV disinfection enhanced coliform bacteria removal. These findings contribute to developing sustainable greywater treatment systems for water reuse, promoting water conservation, and environmental sustainability. This study examined a lab-scale greywater treatment system comprising six filter layers and a PVDF hollow fiber membrane. The system's performance was evaluated with and without UV disinfection to assess its ability to remove physicochemical and microbiological parameters. The treatment system effectively reduced turbidity in all greywater types, exceeding 80% removal after 5 h. BOD_5 removal varied among greywater sources, with the washing basins exhibiting the highest efficiency (87%), followed by the kitchen sink (80%), and the bathroom (63%). COD RE ranged from 62 to 77% after 5 h, with the kitchen greywater showing the highest removal. Without UV disinfection, treated water from the kitchen, bathroom, and washing basins did not meet international irrigation standards but complied with national standards for industrial crops in Vietnam. However, after implementing UV disinfection on greywater from washing basins treated by the filtration system, it complied with the garden irrigation standards set by the US EPA. This study has successfully developed an efficient and cost-effective treatment system for reusing greywater from households in Vietnam's largest city. The system's applicability extends to other developing countries in the Southeast Asian region, given their similar greywater quality and weather conditions. These findings significantly contribute to advancing sustainable and efficient greywater treatment systems, thereby fostering water conservation and promoting environmental sustainability in alignment with Sustainable Development Goal 6.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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