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Performance Evaluation and Reuse Potential of an On-Site Residential Greywater Treatment System for Sustainable Urban Water Management

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Abstract

Rapid urbanization has intensified the imbalance between water demand and freshwater availability, emphasizing the need for decentralized and sustainable water reuse solutions. This study evaluates the performance and reuse potential of an on-site residential greywater treatment system designed for sustainable urban water management. The treatment process consisted of initial settling followed by dual-stage multimedia filtration using two filter storage units (FSU-I and FSU-II). The filtration media comprised sand, activated carbon, zeolite, fine gravel, and coarse gravel, operated under six experimental phases at hydraulic loading rates of 14.00 and 24.00 $m^3/m^2/day$. Sodium hypochlorite (NaOCl) was applied as a final disinfection step prior to reuse. The system demonstrated high treatment efficiency, achieving average removal efficiencies of 95.65 ± 1.95% for turbidity, 82.34 ± 5.84% for biochemical oxygen demand (BOD_5), 96.78 ± 1.87% for total suspended solids (TSS), 76.35 ± 4.11% for chemical oxygen demand (COD_t), and 98.69% for *Escherichia coli*. The treated effluent met reuse standards for non-potable applications such as landscaping, peri-urban agriculture, construction activities, city cleaning, and recreational uses. Implementation of the system resulted in an estimated 65% reduction in daily freshwater consumption, corresponding to an approximate 39.69% decrease in residential water expenditure. Overall, the findings demonstrate that decentralized residential greywater treatment systems can significantly enhance urban water sustainability and support smart city water infrastructure.

Keywords: Greywater reuse; Residential wastewater treatment; Multimedia filtration; Hydraulic loading rate; Urban water sustainability; Smart city planning.

Introduction

Increasing freshwater scarcity, rapid urbanization, and climate variability have intensified pressure on conventional water resources, particularly in developing countries. Urban domestic water demand continues to rise, while available freshwater sources are declining due to overexploitation and pollution. As a result, sustainable water management strategies, including wastewater recycling and reuse, have gained significant attention in recent years (Awasthi, et al. 2024) (WHO 2017). Greywater, defined as wastewater generated from bathrooms, wash basins, laundry, and kitchen activities excluding toilet effluent, constitutes approximately 50–70% of total domestic wastewater volume (Anusha et al. 2025). Although greywater contains lower pathogen concentrations than blackwater, it is characterized by variable organic load, suspended solids, surfactants, oil and grease, and nutrients. (Fangyue Li et al. 2009). If discharged untreated, greywater can pose environmental and public health risks; however, when properly treated, it represents a reliable alternative water resource for non-potable applications such as landscape irrigation, toilet flushing, and groundwater recharge (Oteng-Peprah et al. 2018a) (Oteng-Peprah et al. 2018b) (Fangyue Li et al. 2009) (Friedler, E. 2004). The segregation of household wastewater into greywater and blackwater represents a cost-effective water management strategy that reduces household dependence on municipally supplied potable water, lowers operational and energy costs by decreasing the hydraulic load on centralized wastewater treatment plants, and minimizes expenditure associated with the extraction and distribution of freshwater resources (Fangyue Li et al.2 009) (Eva Eriksson et al. 2002) (Friedler, E et al. 2006).

Finally, Pilot-scale greywater treatment studies are essential to bridge the gap between laboratory research and full-scale implementation. Such systems allow evaluation of treatment efficiency under real hydraulic and pollutant load variations, while also addressing issues related to sludge management, operational stability, and reuse suitability (Suda Ittisupornrat et al. 2023) (Arjen Van de Walle et al.2023). Various treatment technologies including sedimentation, filtration, constructed wetlands, membrane processes, and hybrid systems have been reported in the literature; however, many systems face challenges related to clogging, high maintenance, and energy demand (Satyendra et al. 2025) (Akbari, Z et al. 2025). In household drainage systems, wastewater is commonly segregated into two separate streams through soil and waste stacks, namely blackwater and greywater. Blackwater originates from soil stacks conveying effluent from water closets, including human excreta and urine, whereas greywater is generated through waste stacks from domestic activities such as handwashing, bathing, laundry, and kitchen use. Greywater constitutes a substantial proportion of total domestic wastewater, typically exceeding 70% by volume, and this fraction may increase to nearly 90% in buildings equipped with vacuum toilet systems (Niewitecka K et al. 2025) (Muhammad Ali et al. 2022). Moreover, greywater exhibits lower concentrations of nutrients (nitrogen and phosphorus), pathogens such as Escherichia coli (E. coli), and organic carbonaceous matter, as indicated by reduced Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD), when compared to combined domestic wastewater (Mohan, S et al. 2024) (Samayamanthula et al. 2019).

In addition, household greywater generation and composition are highly variable and depend on parameters including user population, age, climatic conditions, and routine domestic activities.

Greywater characteristics have been widely investigated and documented in previous studies, with representative data from various countries consolidated in Table 1. The data demonstrate substantial variability in greywater quality, reflecting differences in household water-use behaviour, climatic conditions, socio-economic factors, and sanitation practices. From a physicochemical perspective, pH values across the reviewed studies generally remain within a near-neutral range, varying from approximately 6.2 to 8.2, indicating that greywater is typically neither strongly acidic nor alkaline and is suitable for biological or physico-chemical treatment processes without extensive pH adjustment (Birks & Hills 2007), (Pidou et al. 2008). The organic pollution load, represented by Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD_5), shows wide variability. COD values reported in Table 1 range from as low as 96 mg/L to values exceeding 580 mg/L, while BOD_5 concentrations vary between approximately 39 mg/L and 260 mg/L. (Matthew et al. 2023), (Patil et al. 2022), Oteng Peprah et al. 2018b) Parjane & Sane 2011). Total Suspended Solids (TSS) concentrations also exhibit considerable dispersion, with reported values ranging from 17 mg/L to more than 330 mg/L. Elevated TSS levels are often associated with laundry effluent and bathing activities, emphasizing the need for effective pre-treatment or filtration prior to reuse. (Chaillou et al. 2011) (Boyjoo et al. 2013). Nutrient concentrations, expressed as Total Nitrogen (TN) and Total Phosphorus (TP), are comparatively lower than those typically observed in blackwater. TN values in Table 1 range from approximately 4.6 mg/L to 37 mg/L, while TP concentrations vary between 0.01 mg/L and 4.6 mg/L. These findings support the classification of greywater as a lower-nutrient wastewater stream, although nutrient accumulation may still pose eutrophication risks if reused without treatment. (Merz et al. 2007), (Oteng-Peprah et al. 2018) (Al-Wabel 2011), (MEWA Guidelines 2007). Microbiological indicators show notable variability. E. coli concentrations range from non-detectable levels to values as high as 6.0×10^5 CFU/100 mL, while fecal coliform (FC) counts reach up to 1.9×10^6 CFU/100 mL in some cases. (Li et al.2009) (Jokerst et al. 2011) (Boyjoo et al. 2013) These data clearly demonstrate that untreated greywater can pose significant public health risks and requires adequate disinfection before reuse. Overall, Table 1 highlights the heterogeneous nature of greywater characteristics worldwide and underscores the importance of site-specific treatment system design.

Table 2 summarizes the treatment performance of various pilot-scale and laboratory-scale greywater filtration systems reported in the literature. The table compares influent and effluent quality parameters under different filter media, hydraulic conditions, and pre-treatment strategies, providing insight into the effectiveness of decentralized treatment approaches.

Influent turbidity values reported in Table 2 range from approximately 62 NTU to over 940 NTU, reflecting highly variable suspended matter content in raw greywater. Following treatment, effluent turbidity is substantially reduced in most systems, with values commonly decreasing to below 50 NTU, and in some cases reaching values as low as 7–25 NTU, corresponding to removal efficiencies exceeding 70–90%. (Alsaalibi et al. 2017) (Dalahmeh et al. 2012)

Similarly, influent COD concentrations vary widely, from approximately 125 mg/L to more than 1300 mg/L. Treated effluent COD values are significantly lower, often falling within the range of 29–112 mg/L, indicating COD removal efficiencies typically between 60% and 85%, depending on filter media and operating conditions. (Finley et al.2009) (Parjane and Sane 2011) (Balbarini et al. 2020)

Table 1: Comparative analysis of greywater characteristics worldwide

Parameter / country	pH	Turbidity (NTU)	TSS (mg/L)	BOD5 (mg/L)	COD (mg/L)	TN (mg/L)	TP (mg/L)	FC (CFU/ 100 ml)	E. coli (CFU/ 100 ml)	References
UK	6.6–7.6	26.5–164	37–153	39–155	96–587	4.6–10.4	0.4–0.9	3.9×10^5	–	Birks & Hills (2007), Pidou et al. (2008)
Brazil	6.8–7.9	35–120	65–210	95–260	200–480	8–22	0.5–1.8	3.5×10^5	8.7×10^4	M von Sperling et al (2009)
South Africa	6.9–7.5	42–110	180–330	120–205	320–580	12.6	1.8	3.5×10^5	4.2×10^4	Matthew et al. (2023),
India	7.3–8.1	–	100–283	100–188	250–375	–	0.012	–	–	Patil et al. (2022), Oteng Peprah et al. (2018b) Parjane & Sane (2011)
France	7.58	150	125	240	399	9.50	0.42	3.42×10^5	4.76×10^5	Chaillou et al. (2011), Boyjoo et al. (2013)
Bangladesh	6.8–8.2	50–190	95–280	140–260	270–490	8.5	2.0	1.9×10^6	6.0×10^5	Sheikh, M et. al (2018)
Sri Lanka	6.9–7.6	28–74	85–200	100–175	230–440	7.5	0.8–1.6	3.0×10^5	6.1×10^4	Perera, D. D. N et al (2023)
Philippines	7.1–7.8	25–85	90–205	105–195	250–460	11.7	0.9–1.8	4.0×10^5	7.5×10^4	Cinco, E. V et al (2025)
Germany	7.6	29	–	59	109	15.2	1.6	1.4×10^5	–	Merz et al. (2007), Oteng-Peprah et al. (2018a)
USA	6.4	31.10	17	86	–	13.5	4	–	5.4×10^5	Li et al. (2009) Jokerst et al. (2011)
Israel	7.5	1.241	23–34	59–104	148–170	–	–	5.6×10^5	–	Boyjoo et al. (2013)
Ethiopia	6.3-8.1	29 - 375	25-183	110–190	100-700	1.7 – 34.3	0.11- 22.3	0.1- 1.5×10^7	–	Anna Tusiime et al (2022)
Pakistan	6.2	–	155	56	146	–	–	–	–	Mian Jawaduddin Pirzada (
Malaysia	7	–	76	129	212	37	2.4	–	–	Martin (2005)
Saudi Arabia (Riyadh)	7.97	0.95	50–70	50–71	500	7–13.2	3–4.6	–	–	Al-Wabel (2011), MEWA Guidelines (2007)

Table 2. Conventional filter media configurations used in greywater treatment processes												
Type of filter	**Filter characteristics / Media**	**Flux rate**	**Pre-treatment**	**Influent greywater characteristics**				**Effluent greywater characteristics**				**References**
				Influent Turbidity (NTU)	**Influent COD (mg/L)**	**TSS (mg/L)**	**TC (CFU/100 ml)**	**Turbidity (NTU)**	**COD (mg/L)**	**TSS (mg/L)**	**TC (CFU/100 ml)**	
Pressure	Dual media (sand + anthracite)	5.5–30 L/min	Screening	68.2	20.3	–	2.71×E06	51.6	10.7	–	9.8×E05	Alsaalibi et al. (2017)
Gravity	Biochar + gravel	0.1–0.70 L/day	–	–	905	–	1.65×E05	–	71	–	95	Dalahmeh et al. (2012)
Gravity	Ceramic discs + silica sand	–	–	–	–	–	–	–	70	35	91	Matthew et al. (2023),
Gravity	Sand + coconut husk fiber	–	Primary settling	–	290–460	320–550	5.1×E04–8.0×E05	–	150–330	310–600	2.0×E04–4.0×E05	Finley et al. (2009)
Gravity	Gravel + rice husk + activated clay	180 L/hr	Primary settling and aeration	–	340	192	–	–	61	29	–	Parjane and Sane (2011)
Gravity	Zeolite + bio-sand filter	122.5 L/hr	–	–	–	–	7.1×E07	–	16.8	–	3.2×E01	Balbarini et al. (2020)
Gravity	Peat moss + sand	–	–	–	128	–	7.0×E07	–	36.5	–	5600	Tusime et al. (2022)
Gravity	Granular activated carbon + limestone	–	–	–	126	–	7.2×E07	–	42.2	–	5100	Sara Nazif
Gravity	Sand + crushed glass media	–	–	62.5	125.8	289	–	8.6	35.9	22.3	–	Famikaya et al. (2022)
Gravity	Multi-layer composite (sand, gravel, ceramic, biochar)	–	–	–	141	845	230	–	25	112	108	Cinco, E. V et al (2025)
Gravity	Sand + perlite + banana peel bio-adsorbent	16.67 L/hr	Screening	940	1325	1090	2.38×E06	702	710	39.2	9.5×E05	Wakgari et al. (2023)

For Total Suspended Solids (TSS), influent concentrations as high as 1090 mg/L are reported, while effluent TSS values commonly decrease to below 40 mg/L, demonstrating removal efficiencies exceeding 80–95% in systems employing multi-layer filtration or bio-adsorbent media. (Tusime et al. 2022) (Famikaya et al. 2022) (Wakgari et al. 2023)

Microbiological performance also shows substantial improvement. Influent total coliform (TC) counts frequently exceed 10^6 CFU/100 mL, whereas treated effluent values are reduced by one to two orders of magnitude, with reported effluent concentrations as low as 3.2×10^1 to 9.8×10^5 CFU/100 ml, (Finley et al. 2009) (Parjane and Sane 2011) (Balbarini et al. 2020). Although filtration alone achieves significant microbial reduction, the results indicate that additional disinfection may be required to meet stringent reuse standards. Overall, Table 2 demonstrates that gravity-driven and low-pressure filtration systems using sand, biochar, agricultural by-products, and composite media can achieve substantial reductions in turbidity, organic load, suspended solids, and microbial indicators, making them promising options for decentralized greywater reuse.

Fabric-based and non-fabric-based textile media were used for greywater treatment in combination with additional treatment materials. The effectiveness of non-fabric-based textile media for greywater treatment was demonstrated by (Arjen Van de Walle et al.2023). Evidence from independent studies indicates that fabric-based textile media provide enhanced treatment efficiency over non-fabric-based textile media, particularly at minimal discharge conditions. (Karen Campos Rodrigues et al. 2022) (Aklilu Azanaw et al. 2022). The use of a fabric-based fibre microfiltration membrane in domestic wastewater treatment achieved removal efficiencies in turbidity (77.6%), TSS (80.9%), COD (37.5%), and nitrate (NO_3) reduction of 41.4%. (Fan Linhua et al. 2008) (Rena D Salzmann et al 2020). When a fabric-based cotton textile activated with carbon was applied as a standalone filtration unit for domestic wastewater treatment, it demonstrated limited efficacy, with removal efficiencies not exceeding approximately 50 % for BOD_5 and 36 % for COD. However, integrating the textile filter with a Sequencing Batch Reactor (SBR) markedly enhanced effluent quality, yielding BOD_5 and COD removal efficiencies greater than 93 % due to the added biological degradation in the SBR process (Sinem Gunes and Azize Ayol, 2021) (Pravin D. Patil et al 2022).

Thus, the present research focuses to evaluate the treatment efficiency of a household-scale on-site greywater treatment system constructed and operated using actual domestic greywater, to generate realistic insights into its performance and assess its potential for practical on-site implementation. To address water scarcity, a simple and easily maintainable filtration system comprising a settling tank and cotton textile filter media (fabric-based and non-fabric-based) was employed, facilitating the reuse of treated greywater for indirect household purposes and landscape irrigation. The developed filter media system for greywater treatment is easily adaptable to existing households and provides a cost-effective option with simplified operation and servicing relative to other filtration materials. The study assessed the removal efficiencies of the monitored parameters under different filter operating conditions and comparatively evaluated the treatment performance of various filter media combinations.

Description of study Site

The study site comprised a residential apartment building where a pilot household greywater treatment system was installed in the basement; the building includes a ground floor and three storeys with two apartments per level, serving 30 residents. The study site residential building located in Chhatrapati Sambhajinagar, Maharashtra State, India at coordinates (19.8758° N, 75.3393° E). The plumbing layout adopts a source-separation approach for wastewater management. Greywater generated from bathrooms, washbasins, and kitchen activities on each floor is conveyed through a dedicated greywater stack pipe of 75 mm diameter, whereas toilet wastewater is collected independently through a blackwater stack pipe of 110 mm diameter. Fresh water supply to all floors is ensured by a separate 25 mm diameter water supply stack pipe. Both vertical stacks are interconnected at a higher elevation within the basement level, where the combined wastewater is conveyed through a 150 mm diameter sloping lateral pipe to an inspection chamber located in front of the building, and subsequently discharged into the nearest manhole of the municipal sewer network.

Greywater from all floors is collected by gravity in a ground-level sump pit and pumped to a holding tank for flow equalization before entering a settling tank for removal of suspended solids and sludge. The clarified flow then passes over a distribution weir to two parallel filter units, ensuring uniform treatment under both minimum and peak flow conditions. After filtration, the treated greywater is disinfected using calcium hypochlorite ($Ca(ClO)_2$) in a storage and contact tank and subsequently pumped for non-potable reuse, mainly for landscape irrigation.

Finally, water consumption and associated costs for the building were estimated using four years of water billing records (2021–2024). The treatment system was then operated from June 2023 to May 2024 to assess its performance under varying operating conditions, including filtration rate as well as the type and thickness of the filter media. The consideration of both minimum and maximum greywater flow rates ensures hydraulic stability, treatment efficiency, and reliable performance of the system under varying household water demand conditions at the study site.

Table 3 Seasonal variation in household water use, wastewater generation, and greywater discharge

Season	Total water use (lit/c/day)	Water consumption (m^3 / day)	Water tariff (EGP/m^3)	Domestic wastewater (m^3 /day)	Peak greywater flow (lit/ hr)	Lowest greywater flow (lit/ hr)	Mean greywater generation (m^3 /day)	Mean greywater flow (lit/ hr)
Winter	145	4.20	5.10	3.55	190	18	2.10 ± 1.05	88.0 ± 42.5
Summer	170	5.05	5.10	4.30	265	26	3.05 ± 1.40	127.0 ± 58.0

Table 4 Physicochemical and microbiological characteristics of influent greywater

Parameter	Unit	Minimum	Maximum	Mean ± SD
pH	–	6.2	8.3	7.4 ± 0.6
Total suspended solids (TSS)	mg/L	110	240	175 ± 35
Chemical oxygen demand (CODt)	mg/L	210	460	325 ± 75
Soluble chemical oxygen demand (CODs)	mg/L	55	165	115 ± 40
Biochemical oxygen demand (BOD5)	mg/L	150	310	225 ± 60
Escherichia coli	CFU/100 mL	1.2×10^5	4.5×10^5	$(2.8 \pm 1.1) \times 10^5$
Fecal coliforms	CFU/100 mL	1.0×10^5	4.8×10^5	$(2.2 \pm 1.3) \times 10^5$

Evaluation of Greywater Generation Rate and Physico-Chemical Properties

Based on the monthly water meter readings and corresponding utility bills, the total water consumption of the building was systematically quantified along with the associated expenditure, and the compiled results are presented in Table 3. In parallel, comprehensive monitoring of greywater was carried out throughout the study period to determine its quality characteristics. The average values of the key physical, chemical, and biological parameters measured during the investigation are summarized in Table 4.

Layout, Design and Configuration of the Pilot-Scale Greywater Treatment System

The experimental study was carried out in a basement facility of study site under ambient conditions, with temperatures varying from approximately 7 °C during winter to 40 °C in summer. Untreated greywater generated within the building was continuously used throughout the entire investigation, including the start-up phase. As illustrated in Fig. 1, the treatment system comprises a holding tank followed by a settling tank and two sequential filtration units (FSU-I and FSU-II). The treated effluent is subsequently stored in a collection tank, where disinfection is performed prior to its reuse.

Layout and Design of the Pilot Greywater Treatment System

The individual components of the pilot greywater treatment system are described in the subsequent sections, while the complete experimental setup is illustrated in Fig. 2.

Design Details

Flow Rate

Discharge = 2.1 m^3/day (Winter)

Discharge = 3.05 m^3/day (Summer)

Influent Type: Grey water only (from bath, laundry, washbasin)

Treated Output Use: Gardening, toilet flushing, HVAC, etc.

Volume of holding tank: The holding tank had a working volume of 0.75 m^3, which provided approximately 5.45 h of hydraulic buffering under high system flux conditions.

Design and operating parameters of the settling tank:

Parameter	Specification
Tank type	Circular settling tank
Internal diameter (m)	0.55
Surface area (m^2)	0.197
Effective depth (m)	1.6
Working volume (m^3)	0.30
Surface loading rate ($m^3/m^2/day$) – winter	11.99
Surface loading rate ($m^3/m^2/day$) – summer	16.85
Hydraulic retention time (h) – winter	2.87
Hydraulic retention time (h) – summer	2.16
Inlet pipe diameter (mm)	50
Outlet pipe diameter (mm)	50
Sludge withdrawal pipe diameter (mm)	50

Design and operating parameters of the filtration units

Parameter	Specification
Number of filtration units	2 (FSU-I and FSU-II)
Tank cross-section	Circular
Internal diameter (m)	0.30
Filter surface area (m^2)	0.070
Effective depth (m)	1.50
Filter configuration	As shown in Fig. 2
Flux rate, FR_1 ($m^3/m^2/day$)	15.00
Flux rate, FR_2 ($m^3/m^2/day$)	25.00
Excess flow handling	Overflow directed to sump pit
Inlet pipe diameter (mm)	25
Outlet pipe diameter (mm)	25
Fine gravel layer thickness (cm)	20
Gravel size (cm)	1–2
Coarse gravel layer thickness (cm)	20
Gravel diameter (cm)	3-4
Gravel density (kg/m^3)	(1651–1951)
Water depth above media (cm)	52

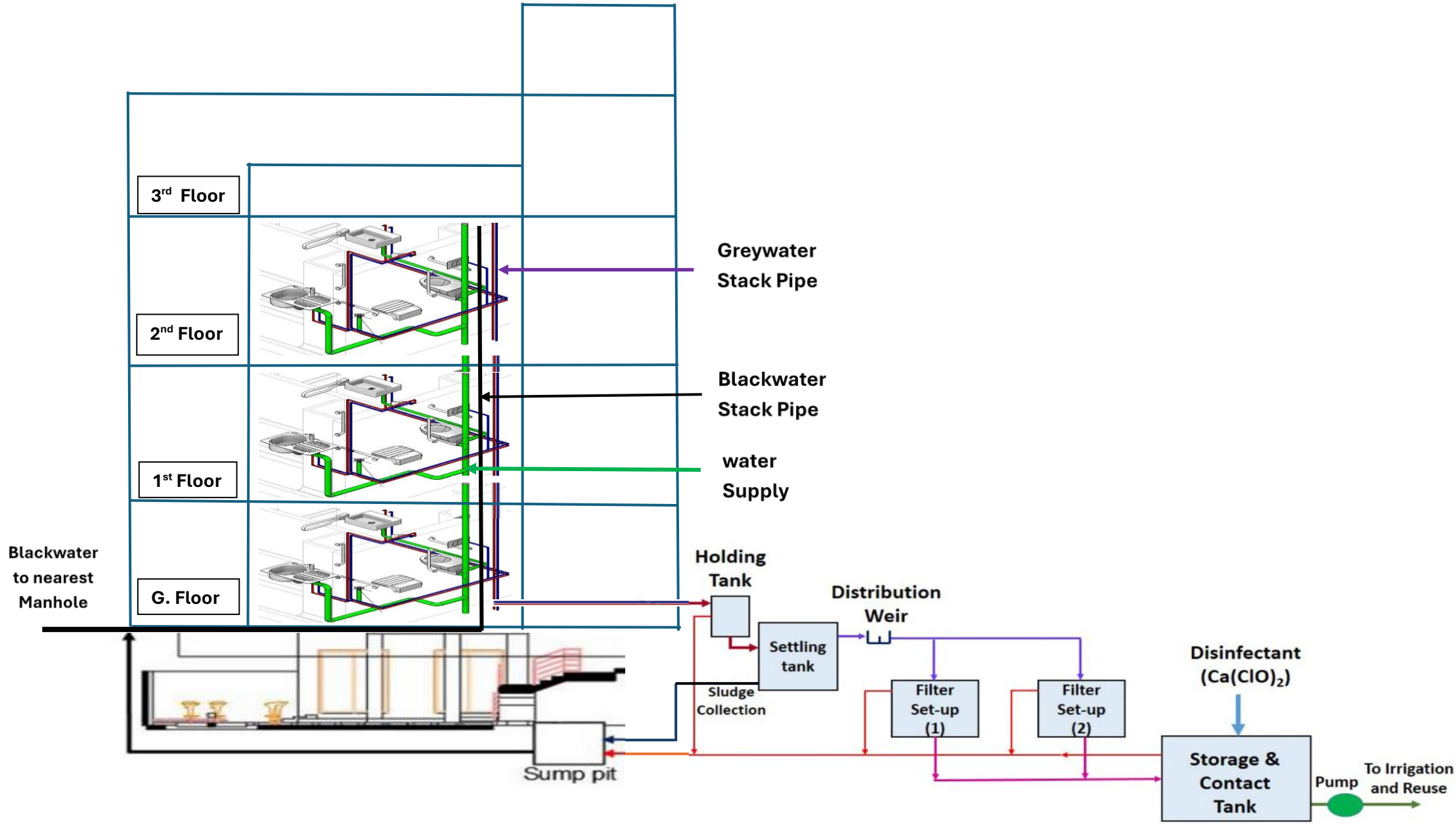
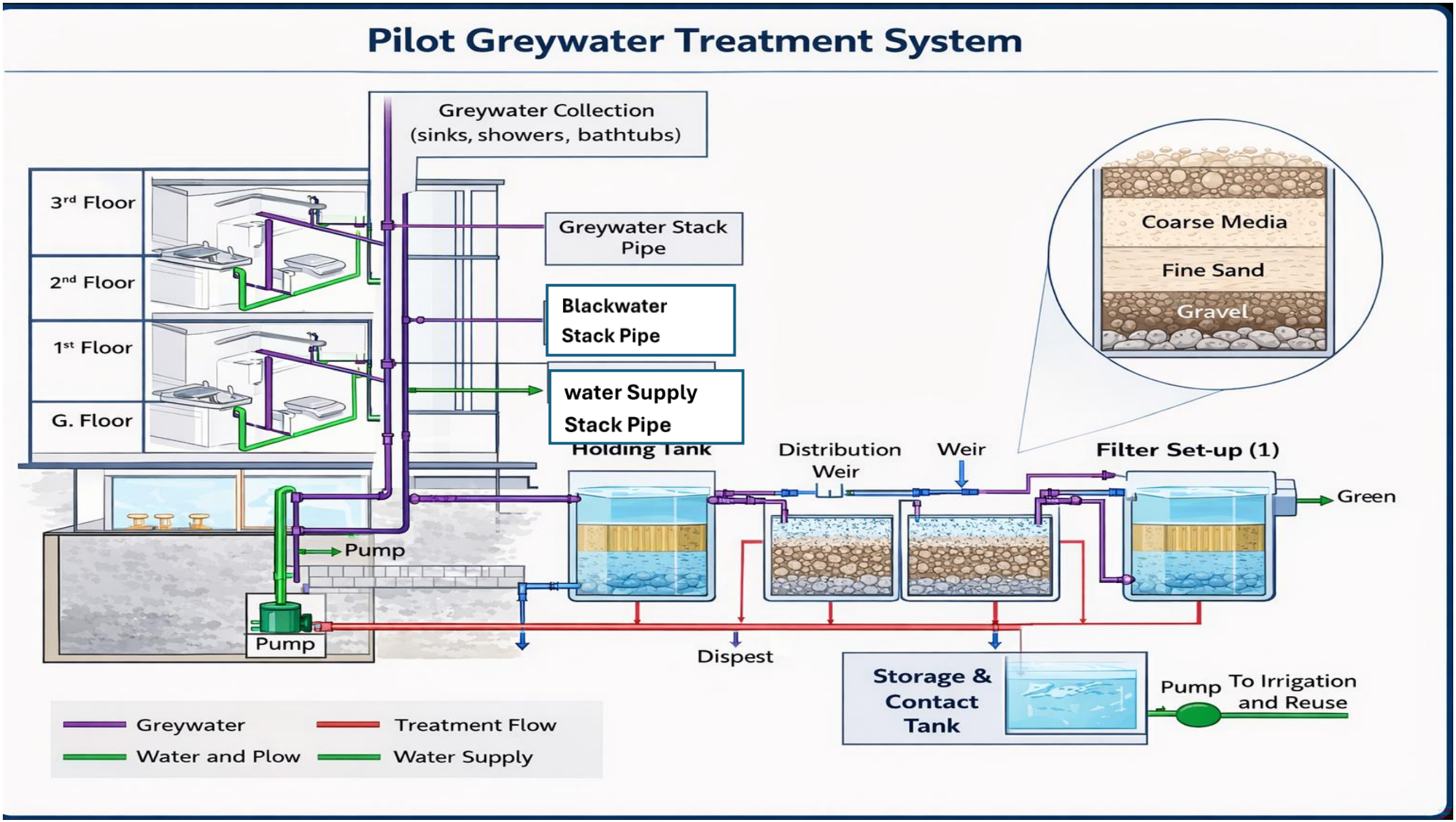
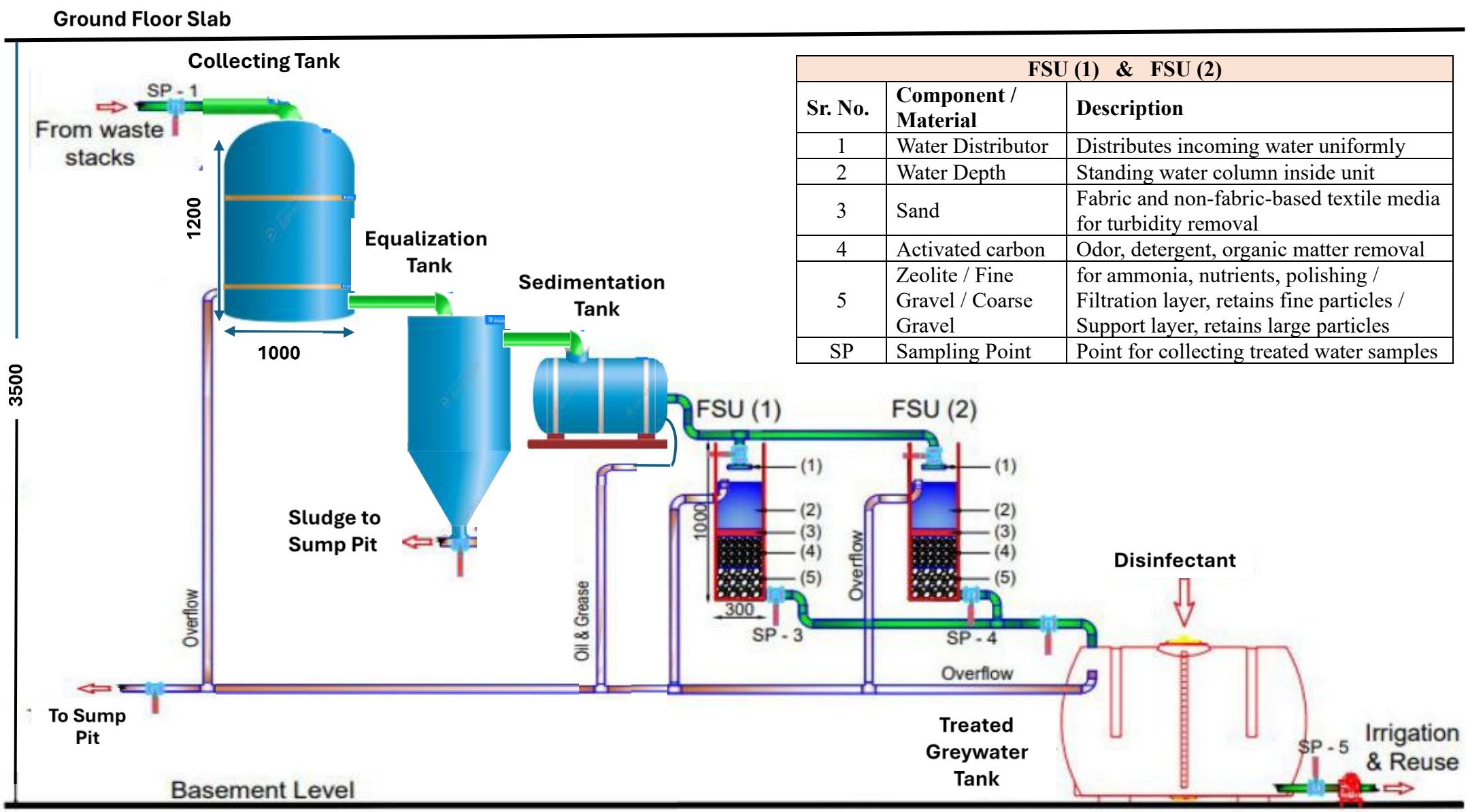


Fig. 1 Schematic illustration of the experimental pilot greywater treatment setup

Pilot Greywater Treatment System





FSU (1) & FSU (2)		
Sr. No.	**Component / Material**	**Description**
1	Water Distributor	Distributes incoming water uniformly
2	Water Depth	Standing water column inside unit
3	Sand	Fabric and non-fabric-based textile media for turbidity removal
4	Activated carbon	Odor, detergent, organic matter removal
5	Zeolite / Fine Gravel / Coarse Gravel	for ammonia, nutrients, polishing / Filtration layer, retains fine particles / Support layer, retains large particles
SP	Sampling Point	Point for collecting treated water samples

Fig. 2 Experimental setup for pilot greywater treatment system

Table 5. Properties of Non-Fabric Geotextile Media

Geotextile Category	Supplier	Product Code	Hydraulic Permeability (cm/s)	Water Flow Capacity ($m^3/m^2/s$)	Effective Opening Size (mm)	Material Thickness (mm)	Areal Mass (g/m^2)
Spun-Bonded Polypropylene (SBP)	Mattex	TB40	0.035	0.035	0.060	2.45	500
High-permeability polyester (PET)	Mattex	NP140	0.020	0.020	0.055	7.80	1200

Note: SBP refers to Spun-Bonded Polypropylene geotextiles, PET denotes High-permeability polyester geotextiles. Water flow capacity is measured normal to the plane of the material, and effective opening size represents the apparent pore dimension.

Table 6. Physical Characteristics of Fabric Cotton Textile Media

Textile Type	Manufacturing Source	Yarn Count (Ne)	Warp–Weft Thread Density (threads/cm)	Effective Pore Size (mm)
Fabric Cotton Textile Media (FCTM)	Local Production	27 × 27	25 × 27	0.018

Geotextiles Filtration

Spun-Bonded Polypropylene (SBP) and High-permeability polyester (PET) non-fabric geotextiles were selected as filter media and tested under two different configurations. The hydraulic and physical properties of each material are presented in **Table 5.** Test specimens were prepared by precisely cutting the geotextile sheets to the specified dimensions for uniform installation. The **table 5** presents the physical and hydraulic characteristics of two categories of non-fabric geotextiles used in filtration applications. Also, the **table 6** presents the structural and hydraulic-related properties of Fabric Cotton Textile Media (FCTM) used as a filtration medium.

Design and operational parameters of the storage and disinfection unit

Parameter	Description
Disinfection approach	Chemical disinfection using calcium hypochlorite
Disinfectant material	Bleaching powder ($Ca(ClO)_2$)
Disinfectant dosage	0.03 g L^{-1}
Storage tank capacity	1.50 m^3
Treated water pump	Grundfos JP 6 B-B-CVBP
Pump operation	Manual
Inlet pipe diameter	25 mm
Outlet pipe diameter	25 mm

Sump-pit parameters and description

All treatment units were provided with overflow connections to safely convey surplus water.
The excess flow, along with the settled sludge from the sedimentation tank, is directed into a common sump-pit. The accumulated contents of the sump-pit are automatically evacuated using two sewage submersible pumps through a 75 mm diameter rising main.
The pumped discharge is first conveyed to a slowdown chamber and subsequently allowed to flow under gravity to an inspection chamber, from where it is finally released into the manhole of the municipal sewer system.

Statistical and analytical greywater parameters measurement with experiment in accredited laboratory

A total of five monitoring locations were established within the treatment system, including positions upstream and downstream of the settling tank, at the outlet of each filtration and separation unit (FSU), and after the disinfection stage. Sample collection was carried out in accordance with the system's operational schedule. All collected samples were examined in the laboratories of the Higher Institute of Engineering, environmental engineering laboratories of Deogiri Institute of Engineering and Management Studies (DIEMS), Chhatrapati Sambhajinagar, Central Laboratory, Navi Mumbai and the laboratories of Chhatrapati Sambhajinagar Municipal Corporation (CSNMC) water supply and sewerage department, Maharashtra, India, following the procedures outlined in standard methods for the examination of water and wastewater. All samples were analyzed following Standard Methods for the Examination of Water and Wastewater (APHA/AWWA/WEF, 2017) in accredited environmental engineering laboratories, including the CSIR-National Environmental Engineering Research Institute (NEERI), NABL-certified municipal wastewater testing facilities in Chhatrapati Sambhajinagar, Maharashtra and Government of India, Phase-II of the Swachh Bharat Mission (2021).

Turbidity was measured using a nephelometric method in accordance with ISO 7027-1. Chemical oxygen demand (COD) was determined by the closed reflux dichromate method following ISO 6060 for both total and soluble fractions. Biochemical oxygen demand (BOD_5) was analyzed using the dilution method (ISO 5815-1), while total suspended solids (TSS) were quantified gravimetrically according to ISO 11923. Microbiological indicators (Escherichia coli and fecal coliforms) were also analyzed. Dissolved oxygen, pH, and temperature were recorded daily using a calibrated multi-parameter analyzer (YSI ProDSS, Xylem Inc., USA). Biochemical oxygen demand (BOD_5) was determined using 300-mL incubation bottles and a temperature-controlled incubator (Memmert IN55, Germany). Chemical oxygen demand (COD) was measured by the closed reflux colorimetric method using a UV–Vis benchtop spectrophotometer (Shimadzu UV-1800, Japan) operating over a wavelength range of 190–1100 nm with a spectral resolution of 1 nm. Escherichia coli and fecal coliforms were quantified using the defined substrate technique with Quanti-Tray and Quanti-Tray/2000 systems.

Statistical evaluation of the dataset was carried out by applying one-way analysis of variance (ANOVA) using GraphPad Prism (Version 9.0; GraphPad Software, San Diego, CA, USA). Where

significant differences were identified, pairwise comparisons were performed using the Holm–Bonferroni method.

Experimental operation framework

The pilot-scale system was operated in six consecutive experimental phases (Phase I–Phase VI), each with an operational period of 60 days. All phases were carried out on both FSU I and FSU II under two different loading rates conditions (LR-1 and LR-2). The system operational schedule and the sampling frequency for each monitored parameter are presented in Table 7. The system was operated continuously, with brief shutdowns of approximately 2 h between phases to allow for media washing or replacement. Occasional interruptions occurred due to minor system malfunctions. Flux was manually regulated using ball valves installed at the outlet of each filter, and the flow rate was determined volumetrically by measuring the collected volume over a known time interval. Oil and grease were removed daily from the holding tank by closing the outlet pipe and allowing the wastewater to overflow for 6 min; the same procedure was applied to the settling tank when oil and grease bypassed the holding tank. During Phases V and VI, WCTF media were evaluated in combination with the PET media previously applied in Phases II and IV, as PET media exhibited superior performance compared with the SBP media used in Phases I and III.

Downstream of the settling tank, a weir was installed to regulate flow distribution and enhance aeration. Water was disinfected with 70% calcium hypochlorite powder at 0.03 g/L, manually stirred to achieve complete mixing. A total of 2000 g of $Ca(ClO_2)$ was used, purchased locally for 374 Indian Rupee.

Table 7 Workflow schedule and data acquisition rate

Phase	Media type	Turbidity	TSS	BOD_5	CODs	CODt	E. coli	FC	Sampling frequency
I	Single SBP layer	18	14	9	5	13	9	9	Twice/week
II	Single PET layer	17	13	9	5	12	8	8	Every 5 days
III	Double SBP layer	19	15	10	6	14	10	9	Once/week
IV	Double PET layer	16	12	8	4	12	8	8	Every 5 days
V	Single PET + FCTM	15	11	7	4	11	7	7	Once/week
VI	Double PET + FCTM	14	10	7	3	10	6	6	Once/week

Experimental Results, Observations and Discussion

Six experimental runs were conducted under controlled conditions as outlined earlier. Throughout each run, samples were collected periodically from five predetermined locations within the treatment system to monitor changes in water quality parameters. These samples enabled a comprehensive evaluation of the system's treatment effectiveness over time. Turbidity sampling

commenced on day three of each run, allowing the system to stabilize from initial start-up fluctuations. The results indicate consistent reductions in turbidity and other measured contaminants, demonstrating the system's capability to treat greywater effectively under varying operational conditions.

Start of operation filter sustainability

The system exhibited a minimal start-up time, both during initial commissioning and transitions between experimental runs. This rapid stabilization is attributed to the predominantly physical treatment processes, which quickly acclimated, aided further by the buffering effects of the holding and settling tanks. As a result, the system operated smoothly, contributing to prolonged filter lifespan. Although no significant clogging of the filters was observed, a gradual decline in hydraulic efficiency was noted, necessitating adjustments such as increasing the outlet valve opening and allowing the water depth above the filter media to rise, peaking after approximately 30 days of continuous operation. At the conclusion of each run, the system was paused for around two hours to perform manual cleaning of the filter media using a water jet before resuming operation. Throughout the nearly one-year experimental period, both filter media types remained structurally intact without the need for replacement.

Initial treatment phase

Consistent across all experimental runs, the Initial treatment phase demonstrated moderate removal efficiencies between 20% and 40%. Despite the modest removal performance, its role was vital in supporting the uninterrupted operation of the filters. The sludge settled during this stage was discharged daily by opening a 50 mm valve for a duration of 10 minutes to transfer solids to the sump pit. The average influent and effluent data along with removal efficiencies for this stage are detailed in **Table 8.**

Table 8 Summary of greywater quality parameters before and after settling tank treatment

Parameter	**Influent Concentration (Average ± SD)**	**Concentration After Settling (Average ± SD)**	**Removal Efficiency (%)**
Turbidity (NTU)	83.5 ± 3.95	61.10 ± 4.00	26.80
TSS (mg/L)	187 ± 14.80	117.00 ± 6.45	37.43
(BOD_5) (mg/L)	212 ± 18.90	169.50 ± 9.00	20.05
(COD_5) (mg/L)	106 ± 8.10	106 ± 8.10	0.00
(COD_t) (mg/L)	318 ± 21.90	244.80 ± 15.50	23.10
E.Coli (CFU/100 mL)	2.42×10^5	2.34×10^5	3.30
FC (CFU/100 mL)	1.82×10^5	1.79×10^5	1.65
(DO) (mg/L)	0.26	0.25	—
pH	7.27	7.22	—

Removal effectiveness of physical water quality indicators

Throughout the monitoring period, pH and DO were recorded daily without applying any operational control. Average influent values of pH and DO were found to be 7.21 ± 0.16 and 1.12± 0.09 mg/L, respectively. The installation of a distribution weir resulted in nearly a 403% rise in effluent DO concentration. Treatment efficiency and effluent greywater quality are strongly governed by variations in pH and dissolved oxygen (DO) levels. Filtration significantly enhanced turbidity and TSS removal; however, removal efficiencies varied with filter media properties and applied flux rates. As shown in Fig. 3, Phase I achieved average turbidity removals of 68.14 ± 7.95% and 64.64± 7.23%, while Phase II recorded higher values of 73.81± 5.59% and 69.31 ± 7.76% at the respective flux rates. Overall, Single PET media (Phase and the lower flux rate (Phase II) demonstrated superior performance. An upward trend in removal efficiency was observed with operating duration, peaking prior to filter media washing, followed by a reduction after system re-operation. The adoption of double-layer media in phase III and phase IV led to a limited enhancement of approximately 5–7% compared to single-layer media. As depicted in Figure 4, TSS removal efficiencies under varying flux conditions ranged between 70.75 ± 4.19% and 88.13 ± 3.88%. The fluctuations observed in the curves are mainly due to periodic media cleaning and redeployment.The use of a double TB media layer did not result in a notable improvement in removal performance compared to the single NP layer, as similar turbidity and TSS removal efficiencies were observed across different flux rates. The average turbidity removal efficiencies achieved with the double TB layer were 72.53 ± 5.12% and 70.67 ± 4.21%, while corresponding values for the single NP layer were 73.79 ± 5.59% and 69.29 ± 4.74%. In the same manner, TSS removal efficiencies for the double TB and single NP layers were recorded as 83.92 ± 2.81%, 79.58 ± 3.98% and 76.28 ± 3.88%, 72.89 ± 4.01%, respectively.

The turbidity and TSS removal efficiencies obtained in the present study are broadly consistent with findings reported in earlier investigations, despite variations in filtration flux and media composition. Kazemi Noredinvand B et al. (2021) observed a turbidity removal efficiency of 90.54% using a multi-media filtration system operating at a flux rate of 122.50 L h^{-1}. In contrast, Famakinwa et al. (2022), Muhammed Nimet Hamidi (2025) reported turbidity and TSS removal percentage of 84.28% and 68.94%, respectively. using a single sand media layer. Rahma Izzatul Fitri et al. (2023) Quispe Bautista, JI (2023) evaluated silica sand and activated carbon media under a flux range of 121–5001 L h^{-1} and reported turbidity and TSS removal efficiencies of 70.76% and 91.95%, respectively. In another study, Spychała and Nguyen (2019) (Zahra Shamsollahi et al 2019) treated greywater using non-fabric geotextiles at a flux rate of 1.1–1.5 cm day^{-1}, achieving TSS removal efficiencies between 68.0% and 89.5 %. The comparative results are provided in Table 2. Thus, Phase V and Phase VI incorporated single and double NP layers along with fabric cotton textile fiber (FCTF) as hybrid filter media and were tested at flux rates FR1 and FR2. The corresponding average turbidity and TSS removal performances are presented in Table 9. The application of fabric cotton textile fiber (FCTF) in conjunction with non- fabric geotextile layers as a hybrid filtration system considerably enhanced removal efficiencies, with turbidity and TSS reductions increasing by approximately 35–45% and 20–30%, respectively. The principal limitation encountered was a reduced filtration rate, necessitating media backwashing. Additionally, operation

under the lower flux rate (FR1) yielded slightly higher removal efficiencies (4–6%) than the higher flux rate (FR2) across all runs.

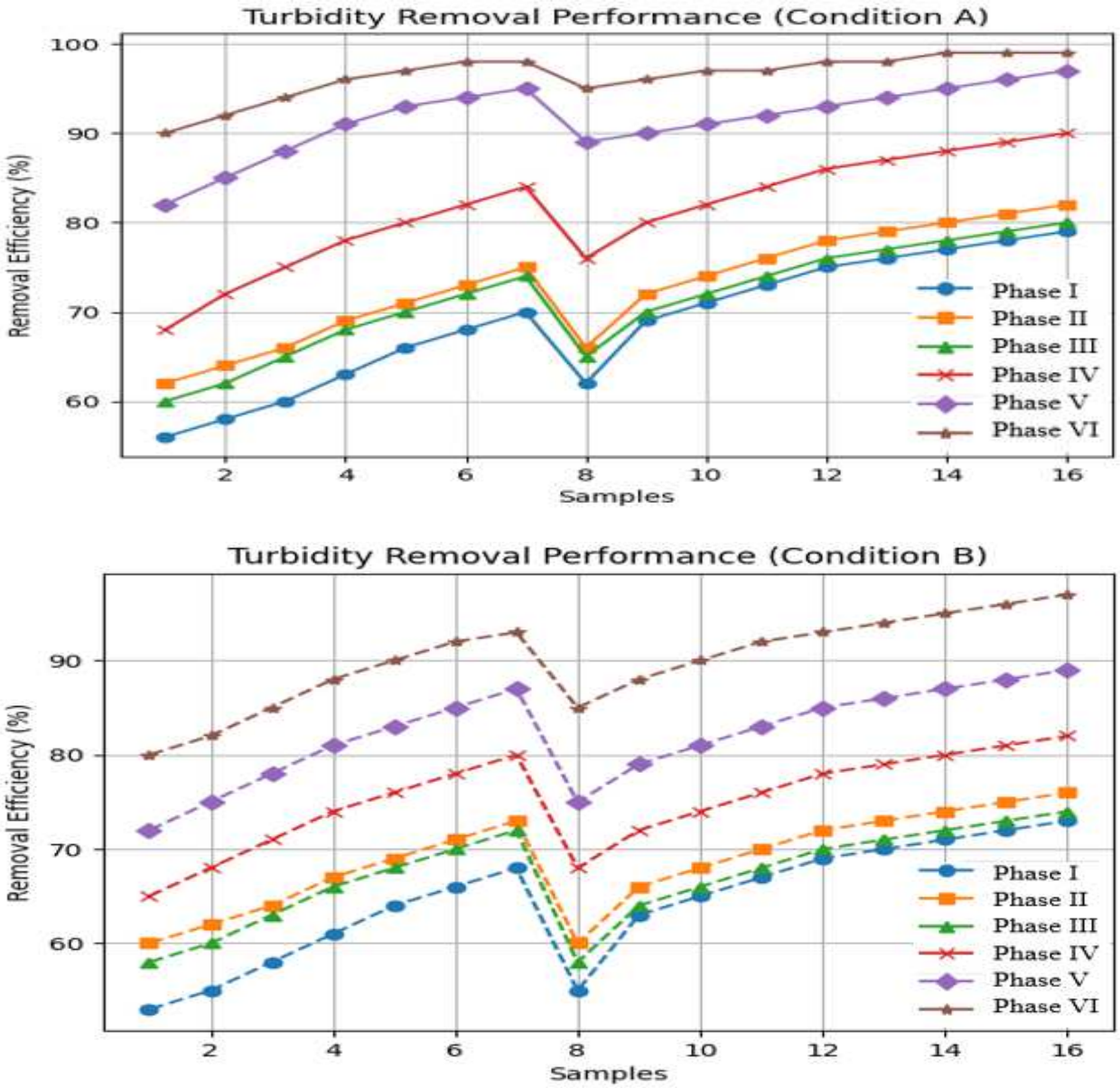


Fig. 3. Turbidity removal ratios obtained for FR1 (a) and FR2 (b) under varying sample conditions.

BOD_5 and COD removal across all experimental runs phase

The application of non-woven geotextile demonstrated satisfactory removal performance for biochemical oxygen demand (BOD) and total chemical oxygen demand (COD_t); however, its effectiveness in the removal of soluble chemical oxygen demand (COD_s) was comparatively limited. Negligible COD_s removal efficiencies were observed during experimental runs phase I to phase IV, while improved removal was recorded in the later stages, attaining **22.71 ± 2.80%** and **28.06 ± 4.29%** in runs phase V and phase VI, respectively. The enhanced treatment performance of the physico-mechanical filtration process can be attributed to the progressive reduction in the effective pore size of both woven and non-woven filter media, resulting from the accumulation and retention of suspended solids, as reported for filtration-based greywater treatment systems

(Eriksson et al., 2002; Jefferson et al., 2004). Furthermore, prolonged operational periods under low hydraulic loading rates likely facilitated biomass growth within the filter matrix, thereby contributing to improved filtration efficiency and partially enhancing soluble COD removal, as observed in similar low-rate filtration and biofiltration studies (Gross et al., 2005; Li et al., 2009).

Figures 5–7 illustrate the progressive improvement in the removal efficiencies of BOD_5, total chemical oxygen demand (COD_t), and soluble chemical oxygen demand (COD_s) resulting from modifications in filter layer configurations and applied flux rates across all six experimental runs. The removal efficiencies for BOD_5, COD_t, and COD_s summarized in Table 10 are consistent with values reported in comparable greywater treatment studies employing filtration-based systems and low-rate physico-mechanical processes (Jefferson et al., 2004; Friedler et al., 2006). The fluctuations observed in the performance curves can be attributed to periodic washing and subsequent reinstallation of the filter media, which temporarily altered the effective pore structure and filtration dynamics before system performance stabilized Manuel Algarra et al (2001).

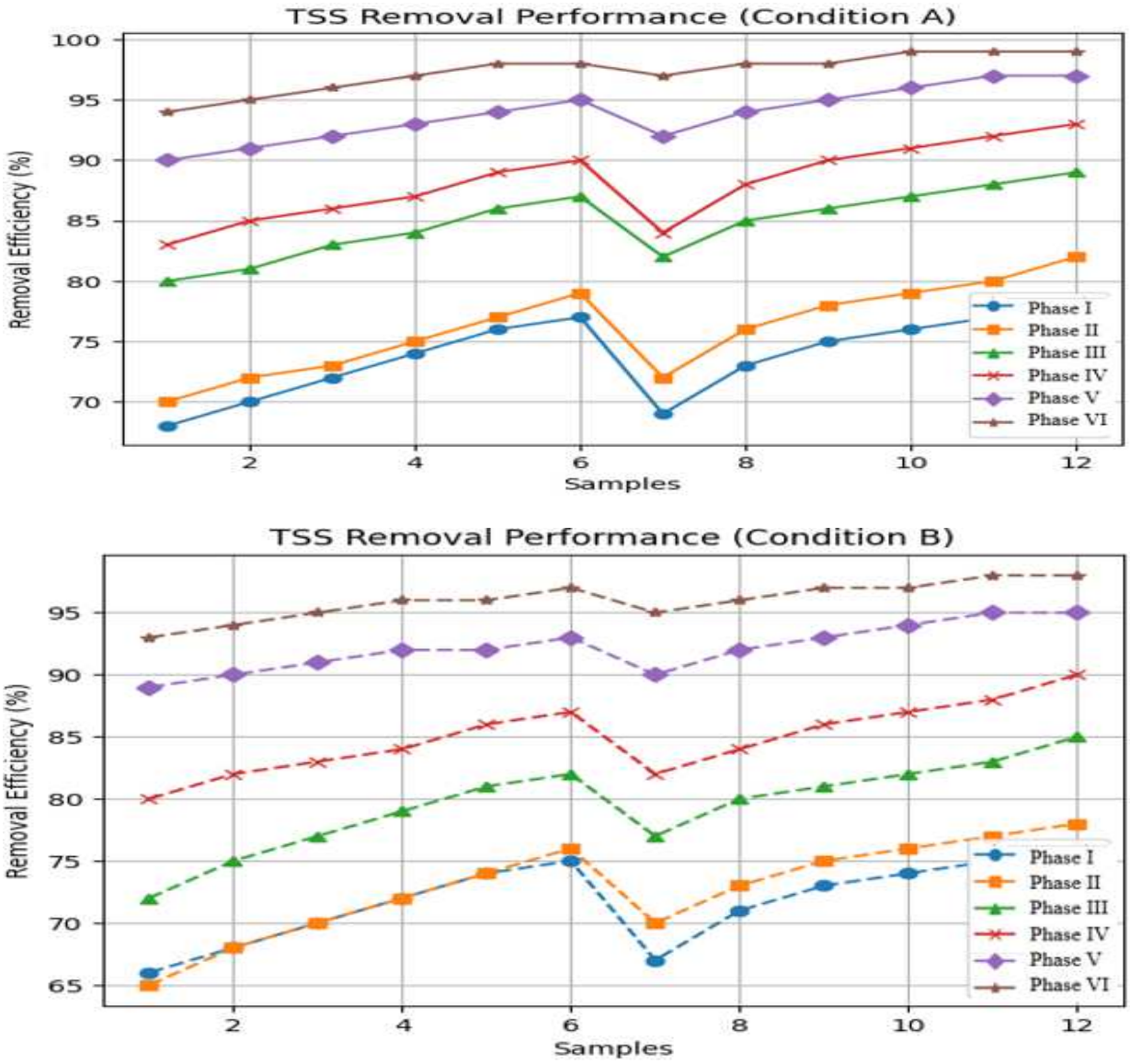


Fig 4 Comparative TSS removal performance under filtration regimes **FR1 (a)** and **FR2 (b)**, under varying operational conditions.

Table 9 Removal performance of turbidity and total suspended solids using fabric cotton textile fiber (FCTF) as filtration media

Run (Phase)	Media configuration	Flux rate	Turbidity (%)	TSS (%)
Phase V	Single NP layer + (FCTF)	FR1	88.45 ± 4.62	92.18 ± 1.74
		FR2	84.96 ± 5.88	90.12 ± 1.45
Phase VI	Double NP layer + (FCTF)	FR1	95.87 ± 1.96	96.72 ± 1.54
		FR2	89.74 ± 4.91	94.26 ± 1.27

The operation at lower flux rates and extended filtration periods improved removal efficiencies but reduced the hydraulic throughput of the filtration system. Effluent quality from runs phase I – phase IV did not meet the reuse and irrigation limits specified by the Indian standards. The use of double-layer filter media (phase III and phase IV) instead of single-layer configurations (phase I and phase II) resulted in only a marginal increase in removal efficiency (approximately 6–8%).The needle-punched (NP) non-fabric geotextile consistently outperformed the thermally bonded (TB) geotextile, leading to its integration with fabric cotton textile fabric (FCTF) as a hybrid filtration medium. This configuration, applied in runs phase V and Phase VI, achieved substantially higher removal efficiencies (approximately 22–32%) compared with earlier runs, with only run phase VI producing effluent that complied with the Indian reuse and irrigation standards.

The removal efficiencies obtained for BOD_5 and total chemical oxygen demand (COD_t) in the present study fall within the range reported in comparable greywater treatment investigations, particularly when differences in filter media characteristics, number of layers, and applied flux rates are considered. For example, Jefferson et al. (2004) reported BOD_5 and COD removal efficiencies in the range of 55–80% using filtration-based greywater treatment systems operated under low hydraulic loading conditions. Similarly, Friedler et al. (2006), Aluvihara, S. et al. (2025) demonstrated that media type and filtration rate significantly influence organic matter removal, with BOD_5 and COD reduction efficiencies comparable to those observed in the present study. These findings support the observed performance trends and confirm the strong dependence of organic removal efficiency on filtration media properties and operational parameters.

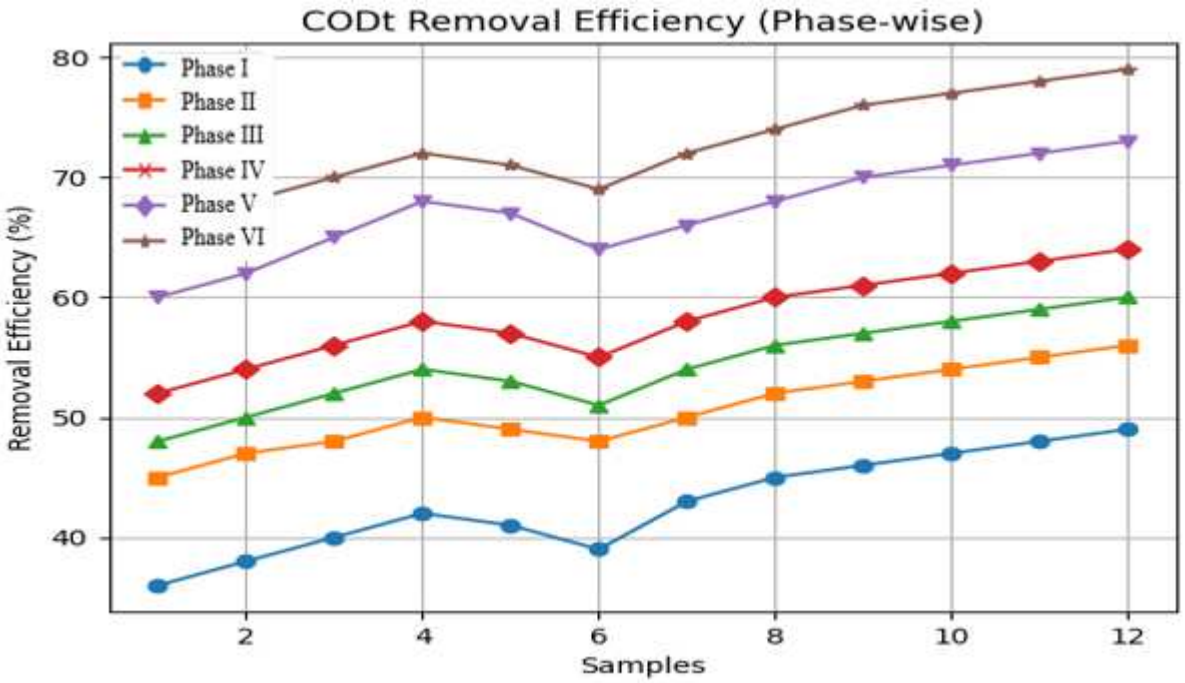
Pilot-Scale Evaluation of E. coli and Fecal Coliform Removal

scherichia coli and fecal coliforms were selected as indicator organisms to evaluate the microbial quality of greywater, as commonly recommended for assessing sanitary safety in water reuse applications (WHO, 2006; APHA, 2017) (Sofiane El Barkaoui et al 2023). The findings revealed that post-treatment disinfection was necessary prior to reuse, since the filtration process alone achieved only a limited microbial reduction of approximately 1–2 log units, consistent with earlier observations reported in similar greywater treatment studies (Gross et al., 2005; Oteng-Peprah et al., 2018a). Calcium hypochlorite [$Ca(ClO)_2$] was employed as the disinfectant due to its cost-

effectiveness and widespread availability. Experimental trials indicated that a dosage of approximately 0.04 g/L was sufficient to achieve the required level of disinfection during Phase V and Phase VI. After disinfection, *E. coli* and fecal coliform concentrations were reduced to 9.82 × 10^2 and 1.1 × 10^3 CFU/100 mL, corresponding to removal efficiencies of 99.60% and 99.46%, respectively, thereby meeting recommended microbial reduction targets for non-potable reuse (WHO, 2006) (Xiaohui Li et al 2023).The treated greywater met the microbiological reuse criteria outlined in Indian standards, with pathogen levels effectively controlled primarily through the applied disinfectant dose rather than the baseline treatment system performance. Recent research has similarly reported that disinfection intensity is a key factor in achieving adequate pathogen reduction in greywater reuse applications (Reynaert, E et al (2024); Xueli Ren et al (2023)

Performance and Impact Analysis of Treated Greywater Reuse

The scope of greywater reuse in the present work was confined to landscape irrigation around the building, as reuse within residential units could not be evaluated due to the absence of dedicated internal piping and plumbing infrastructure for distribution (Li et al., 2009; Eriksson et al., 2002). Engaging stakeholders through structured consultation and awareness programs would facilitate a clearer understanding of public perceptions and acceptance of treated greywater reuse. As reuse applications extend beyond landscape irrigation to include activities such as construction works and vehicle washing, it becomes essential for regulatory authorities to proactively enhance community awareness. These initiatives should emphasize technical feasibility, potential environmental and health impacts, and the importance of conducting comprehensive environmental and public health assessments prior to implementing direct reuse practices (Dolnicar et al., 2011; Friedler & Hadari, 2006; World Health Organization, 2006).



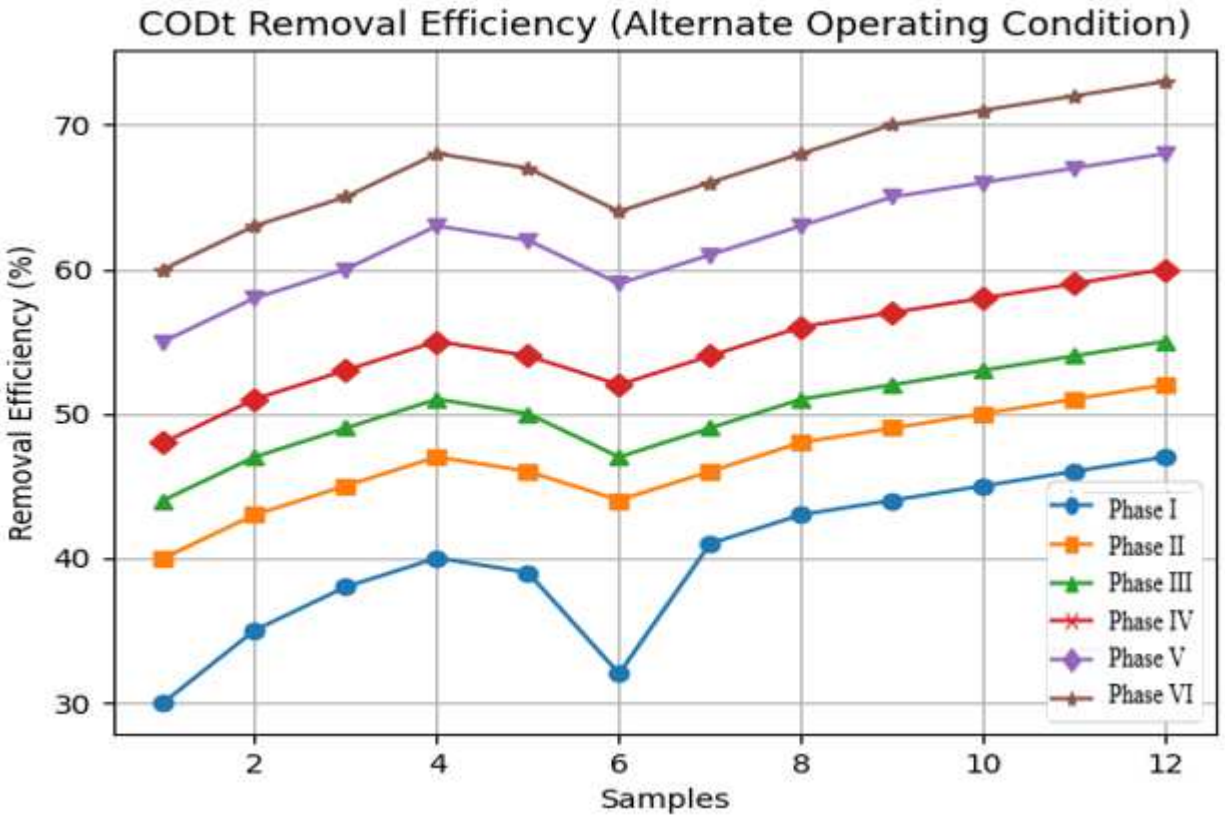


Fig. 6. Variation in CODt removal performance observed during (a) FR1 and (b) FR2 operational regimes.

Cost Estimation for Treated Greywater

The cost estimation focused on Phase V and Phase VI, as these runs generated treated greywater of sufficient quality for reuse. All experimental phases (Phase I–Phase VI) showed comparable costs, with differences arising only from the filter media, whose contribution was insignificant relative to the overall system cost. Due to the absence of a separate plumbing arrangement for toilet flushing, the treated greywater was reused solely for on-site lawn irrigation. A design life of 15 years was assumed for the cost evaluation, in accordance with commonly adopted practice in India for similar treatment facilities. While no media replacement was required during the experimental period, an additional 15% cost was included to account for replacement during long-term operation. The main steps involved in the cost analysis are outlined below.

Cost of irrigation water

The unit cost of irrigation water was taken as 9.35 ₹/m^3. With a daily irrigation demand of 1.60 m^3, the resulting daily expenditure for irrigation water was calculated as:

$$\text{Total irrigation water cost} = 9.35 \times 1.60 = 14.96 \text{ ₹/day}$$

Treated Greywater – Economic Evaluation (Analytical Form)

Treated Greywater Quantity: The treatment system produced an average of 3.10 m^3 of treated greywater per day.

Filter Media Cost

a) The cost of non-fibre geotextile filter media (thermal-bonded and needle-punched) ranged from 115.79 to 233.68 ₹/m².

b) The Fibre cotton textile fiber (FCTF) filter media cost was 116.84 ₹/m².

Capital Cost of Treatment System

The total installation cost of the greywater treatment system, including filter media, was estimated at ₹ 9736.

Assumed System Lifetime

The economic analysis was carried out for a design life of 15 years, which was considered appropriate for similar treatment systems.

Investment Cost per Unit Volume

The capital cost per cubic meter of treated greywater was calculated as:

$$\text{Investment cost} = \frac{9736}{3.10 \times 15 \times 365} = 0.57 \text{ ₹/m}^3$$

Operation and Maintenance (O&M) Cost

The O&M cost was mainly associated with the disinfection process, as the system operated without any energy consumption.

Disinfectant Cost

Based on the quantity of disinfectant used, the unit disinfectant cost was estimated to be ₹0.193 per gram

The total operation and maintenance cost ($C_{O\&M}$) was calculated by incorporating an additional 15% of the disinfectant cost, expressed as:

$$C_{O\&M} = 0.03 \times 1000 \times 0.193 = 5.79 \text{ ₹/m}^3$$

The total unit cost of treated greywater was calculated by combining the base treatment cost with the disinfection cost and incorporating additional operation and maintenance (O&M) expenses. This can be expressed mathematically as:

$$C_{\text{TGW}} = (C_{\text{base}} + C_{\text{dis}}) \times (1 + \alpha)$$

$$\text{CTGW} = (0.57+5.79) \times 1.15 = 7.22 \text{ ₹/m}^3$$

The daily cost of treated greywater used for irrigation was then estimated based on the daily irrigation demand:

$$C_{\text{irr}} = Q_{\text{irr}} \times C_{\text{TGW}}$$

$$\text{Cirr} = 1.5 \times 7.22 = 10.83 \text{ ₹/day}$$

Table 10 Removal efficiency (%) of BOD_5, COD_t and COD_s under different runs and flux rates

Run	Flux rate	BOD_5 (%)	COD_t (%)	COD_s (%)
Phase I	FR1	46.92 ± 4.15	44.10 ± 4.28	1.48 ± 0.41
	FR2	41.78 ± 4.02	40.95 ± 5.12	1.26 ± 0.46
Phase II	FR1	55.84 ± 3.98	50.62 ± 2.91	2.15 ± 0.51
	FR2	51.37 ± 4.21	46.88 ± 3.05	1.92 ± 0.48
Phase III	FR1	64.21 ± 2.85	56.03 ± 2.76	2.59 ± 0.34
	FR2	61.05 ± 3.12	52.74 ± 2.89	2.41 ± 0.29
Phase IV	FR1	71.86 ± 3.05	61.12 ± 3.32	2.95 ± 0.39
	FR2	67.44 ± 2.91	57.26 ± 2.58	2.78 ± 0.41
Phase V	FR1	75.63 ± 4.02	70.12 ± 4.45	17.21 ± 2.18
	FR2	72.11 ± 3.21	66.34 ± 3.92	15.74 ± 2.36
Phase VI	FR1	82.45 ± 4.18	76.28 ± 3.74	29.34 ± 4.12
	FR2	77.08 ± 3.46	72.64 ± 3.05	23.86 ± 2.65

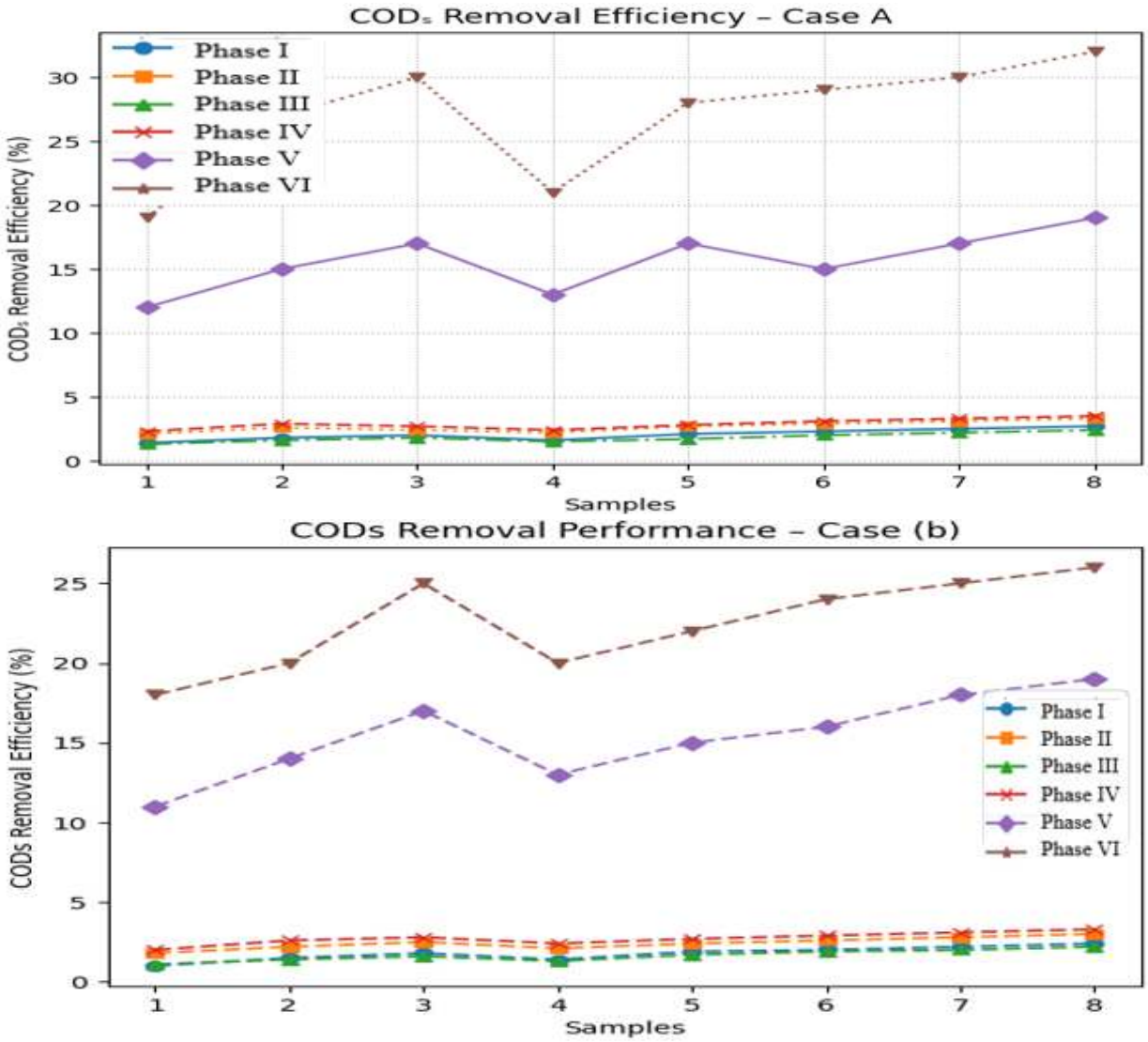


Fig. 7. Comparative performance of soluble COD (CODs) removal for (a) filtration regime FR1 and (b) filtration regime FR2.

The daily monetary savings achieved by substituting potable water with treated greywater were determined by comparing their respective daily costs:

$$S_{\text{daily}} = C_{\text{potable}} - C_{\text{TGW}}$$

$$S_{\text{daily}} = 17.96 - 10.83 = 7.13 \text{ ₹/day}$$

The monthly savings were estimated, assuming continuous daily use over a 30-day period:

$$S_{\text{monthly}} = S_{\text{daily}} \times 30 = 7.13 \times 30 = 213.90 \text{ ₹/month}$$

The percentage cost savings resulting from the use of treated greywater instead of potable water were calculated as:

$$\text{Cost savings (\%)} = \left(\frac{S_{\text{daily}}}{C_{\text{potable}}}\right) \times 100$$

$$\text{Cost savings (\%)} = \left(\frac{7.13}{17.96}\right) \times 100 \approx 39.69\ \%$$

Based on the preliminary cost assessment, the application of treated greywater resulted in an approximate 39.69 % reduction in irrigation water expenses (Xu Zhou et al 2018). A significant portion of the treatment cost was attributed to the disinfectant stage. Replacing chemical disinfection with ultraviolet irradiation or biological filtration, which are generally more economical, could further enhance overall cost savings (Hamidi et al. 2025; Aluvihara et al. 2025) (Satyendra et 2025).

Conclusion

Increasing population growth and constrained freshwater availability necessitate greater reliance on reclaimed water for irrigation and non-potable applications. Agricultural irrigation may contribute up to 65–75% of total water demand when domestic and industrial uses are included. The development of simple, cost-effective on-site treatment systems is essential to enable greywater separation and reuse at the source. Adoption of such systems depends on reliable production of safe treated water, low operation and maintenance demands, and demonstrable cost benefits.

An experimental assessment of on-site household greywater treatment was conducted using pre-settling followed by filtration through non-fibre geotextiles with varying physical properties and operational flux rates. A fibre cotton textile layer was additionally employed in the final two experimental phases to evaluate its performance. The main conclusions obtained from this investigation are presented below:

- Greywater pretreatment using a settling tank resulted in a 25–45% reduction in pollution load. The incorporation of both holding and settling tanks improved hydraulic stability and ensured flexible system operation.
- The physical treatment approach resulted in very limited COD removal, with near-zero values recorded during the initial four phase runs. Improved performance was observed in runs incorporating double layers of non-fibre (NF) geotextiles and fibre cotton textiles,

achieving approximately 30% COD reduction. This improvement is attributed to biofilm formation within the filter media during the prolonged 30-day operational period.

- Runs phase V and phase VI, which incorporated fibre cotton textile media together with double layers of non-fibre (NF) geotextiles, demonstrated the best treatment performance. removal efficiencies of 95.65 ± 1.95% for turbidity, 82.34 ± 5.84% for BOD_5, 96.78 ± 1.87% for TSS, 76.35 ± 4.11% for CODt, and 98.69% for E. coli, were achieved, and the treated effluent from these runs satisfied the Indian reuse standards.
- The proposed filtration system demonstrates practical operability with low operation and maintenance demands, requiring minimal financial input, technical expertise, and energy consumption.
- The treatment system achieved acceptable removal efficiencies for primary pollution indicators, balancing its straightforward design and low capital costs with minimal operation and maintenance demands, including labor, energy, and disinfectant requirements.
- The replacement of a single non-woven geotextile layer with double layers enhanced removal efficiency by approximately 7–8%.
- After 30 days of operation, representing the filter validity period, the media in all runs were manually washed using a water jet following a noticeable decrease in flow rate. The majority of suspended solids were retained on the media surface, forming a filter cake, while some solids remained attached to the media even after cleaning.
- The application of treated greywater for irrigation led to a cost reduction of nearly 39.69 %. Further reductions in operational costs could be achieved by replacing calcium hypochlorite with more economical disinfection methods.
- The evaluation of treated greywater reuse within the building was not undertaken because dedicated plumbing connections were not available, preventing assessment of odor, color, and user acceptance.
- More than 65% of household wastewater is classified as greywater, and its treatment and reuse can potentially reduce household water consumption and economic costs by over 55%.

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Authors' Contributions

Akram Salim Pathan conceived and designed the study. Experimental setup, data collection, and analysis were performed by Akram Salim Pathan and Milind L. Waikar. All authors contributed to interpretation of results, manuscript preparation, review, and final approval of the submitted version. All authors agree to be accountable for all aspects of the work.

Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Ethical Approval

This article does not contain any studies involving human participants or animals performed by any of the authors. Therefore, ethical approval is not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Competing Interests

The authors declare that they have no competing interests or personal relationships that could have appeared to influence the work reported in this paper.

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