Subramanian, P.S. G., Raj, A. V., Jamwal, P., Connelly, S., Yeluripati, J., Richards, S., Ellis, R. and Rao, L. (2020) Decentralized treatment and recycling of greywater from a school in rural India. *Journal of Water Process Engineering*, 38, 101695.

(doi: 10.1016/j.jwpe.2020.101695)

This is the Author Accepted Manuscript.

There may be differences between this version and the published version. You are advised to consult the publisher's version if you wish to cite from it.

https://eprints.gla.ac.uk/224002/

Deposited on: 16 October 2020

Enlighten – Research publications by members of the University of Glasgow
http://eprints.gla.ac.uk

# Decentralized Treatment and Recycling of Greywater from a School in Rural India

P S Ganesh Subramanian[1], Anjali V Raj[2], Priyanka Jamwal[2], Stephanie Connelly[3], Jagadeesh Yeluripati[4a], Samia Richards[4b], Rowan Ellis[4c] and Lakshminarayana Rao[1*]

[1]Center for Sustainable Technologies, Indian Institute of Science (IISc), Bangalore, India

[2]Centre for Environment and Development, Ashoka Trust for Research in Ecology and the Environment (ATREE), Bangalore, India

[3]Division of Infrastructure and Environment, James Watt School of Engineering, University of Glasgow, Glasgow G12 8LT, UK

[4a]Information and Computational Sciences, The James Hutton Institute, Craigiebuckler, Aberdeen, AB15 8QH, Scotland, UK.

[4b]Environmental and Biochemical Sciences, The James Hutton Institute, Craigiebuckler, Aberdeen, AB15 8QH, Scotland, UK.

[4c]Social, Economic, and Geographical Sciences Department, The James Hutton Institute, Craigiebuckler, Aberdeen, AB15 8QH, Scotland, UK.

## Abstract

Rural areas in developing countries face the twin challenges of water scarcity and risk of groundwater contamination due to lack of water treatment options. A decentralized greywater treatment system for reuse is an option that addresses both of these challenges. This study reports the performance of a decentralized greywater treatment and reuse system which was constructed and operated for over 12 months in a government-managed school in rural India. The handwash and kitchen wash wastewater streams were treated separately due to differences in the initial greywater characteristics. The treatment stages included pre-treatment using

---

[*] Corresponding author: Dr. Lakshminarayana Rao, Assistant Professor, Center for Sustainable Technologies, Indian Institute of Science, Bangalore, India
email: narayana@iisc.ac.in

screens and grease traps, slow sand biofiltration combined with anaerobic sludge bioreactor, and aeration before the final ozone-based disinfection stage. The treated water at the end of all these stages was used for toilet-flushing in the school. The treatment system was operated for one year and sampling was performed to investigate the system performance. The overall treatment system showed removal efficiencies of 99%, 98%, 66%, 73%, 98%, 96% and >99.99% for the parameters of turbidity, total suspended solids, nitrate, total phosphorus, biological oxygen demand (5 days), chemical oxygen demand and fecal coliform respectively. This study quantifies the performance of each subsystem and demonstrates for the first time that a decentralized greywater treatment can be operated effectively and economically in a rural Indian setting.

**Keywords:** decentralized, greywater, water treatment, water recycling, biofiltration, plasma ozonation

# 1 Introduction

With increasing population, climate change and expanding pressures on water resources, much of the world faces a major water crisis. Globally, water shortages are estimated to affect more than 4 billion people annually[1]. India occupies only 2.4% of the world's total land area yet supports over 17.5% of the global population[2]. The total freshwater resource of the country is only 4% of the world's total utilizable water resource[3], which is disproportionately low for the current population. In India, over 600 million people face high to extreme water scarcity, with water contamination estimated to impact as much as 70% of the country’s utilizable water resource[4]. Currently, the disparity between water supply and demand is widening due to increasing water scarcity[5],[6], population growth, contamination of available surface water sources and depleting groundwater reserves. As this disparity worsens, there is a growing need for technologies that can address the interactions between poor water quality and insufficient water quantity[7,8]. Despite the extensive scientific and technological advances, the discharge of untreated wastewater (WW) in India still poses environmental and human health risks[9]. Treatment technology exists, but today these technologies are based on the conventional large-scale centralized WW treatment plants, where WW is collected from various sources and brought to a centralized WW treatment plant through extensive pipe networks[10]. Decentralized, efficient, on-site treatment and reuse of WW in general and greywater in particular, has the potential to realize the dual benefits of reducing consumption of freshwater and sustainably managing WW, especially in rural and peri-urban areas[11]. Though the reuse of greywater has a lot of potential, there are obstacles to its reuse, including but not limited topublic health concerns and human perceptions of using treated water[12].

Wastewater generated from households typically consists of blackwater (BW) and greywater (GW). BW is defined as wastewater produced in toilets, whereas freshwater soiled by use in laundry, baths, showers, hand washbasins, dishwashers, and kitchen sinks is called GW [13]. Contaminants present in the GW includes oil, food waste from kitchen water and surfactants from all household cleaning and personal care products. Relative to BW[14], GW has characteristically low suspended solids[15], pathogens and nitrogen[16]. The quality of supplied freshwater and the type of water distribution system (continuous vs intermittent supply) is known to affect the composition of GW[17]. Due to these characteristics, GW represents a huge potential for domestic water savings through reuse. In many parts of the world, GW is reused for landscape irrigation, toilet flushing, gardening and other non-potable uses[12,16,18,19]. This has been supported by regulation and financial incentives that support a transition to water reuse technologies[20].

Greywater treatment for reuse has utilized one or more technologies such as:

Filtration (anaerobic, activated carbon, biofilm, fiberglass, Filtralite®, horizontal, oil shale ash, sand, slate waste, vertical, volcanic ash, etc.), rotating biological contractors, sedimentation, reed beds, constructed wetlands, microbial fuel cells, coagulation, granular activated carbon adsorption, aeration and disinfection (UV, chlorination, etc)[21–31]. Bolton et. al. showed that there is also potential to obtain electrical energy from treating GW by using constructed wetlands and microbial fuel cells followed by biological sand filtration for reuse[31].

Reuse of GW for non-potable purposes remains relatively uncommon in India, partly owing to unproven technologies, high costs for installation, operation and maintenance of such systems, but also because of the social sensitivities that surround human interactions with wastewater [32]. Realizing the full potential of GW reuse requires cost-effective, proven and efficient approaches to treatment that are adaptable to site-specific hydro-social conditions[33].

This work reports the design and performance of a decentralized, gravity-driven GW treatment and reuse system designed by integrating different technologies specifically for a government school in rural India. The GW recycling system was co-designed by engaging stakeholders in a demand-driven approach. The treatment scheme used disinfection techniques such as ozonation by installing ozonators specifically designed for the rural Indian setting. This was done to ensure the system was not reliant on disinfection chemicals, such as chlorine, which need to be procured from a nearby city or town. . This study is uniquebecause not only does it demonstrate the successful functioning of a decentralized GW treatment plant but also captures and compares the performance of various treatment options. The system was operated for over 12 months by students and staff in a rural government school. The performance of each of the different treatment modules is quantified. The treated GW was recycled and its effect on the school's annual water budget is reported.

# 2 Materials and methods

## 2.1 Study location and size

This study was conducted in the Berambadi Primary School ($11^0 45' 44''$ N; $76^0 34' 03''$ E) located in Berambadi village (Population of 2982 as of 2011)[34], Chamarajanagar district in the Indian state of Karnataka. The school is located in the Berambadi watershed ($11^0 43' 00'' - 11^0 48' 00''$ N; $76^0 31' 00'' - 76^0 40' 00''$ E), which is classified as AW (Tropical wet and dry or Savannah Climate) based on the revised $Köppen - Geiger$ climate classification. The area receives an average annual rainfall of 1000 $mm$ [35].

Typically, schools do not generate as much per capita GW as domestic households, owing to the absence of GW sources such as laundry and showers. The government-run schools in India operate a mid-day meal initiative where nutritious food is cooked at the school and provided to the students for lunch. The Berambadi school generated GW from its hand wash (HW) and kitchen wash (KW) sinks. During this study, the school had about 187 students and 10 staff. The HW sinks which were used by the students and staff were located at a slightly higher elevation compared to the KW sink. The GW treatment system utilized this difference in elevation for gravity flow. This study was conducted for a total period of one full academic year, which included 50 days of summer break between April and June and a two week Navaratri/Dasara break at the beginning of October.

## 2.2 System description

Figure 1 shows the block diagram of the stages of treatment for HW and KW greywater. The HW and KW streams were separated owing to the difference in their composition. The composition of the HW and KW greywater is discussed in Section 3.1.

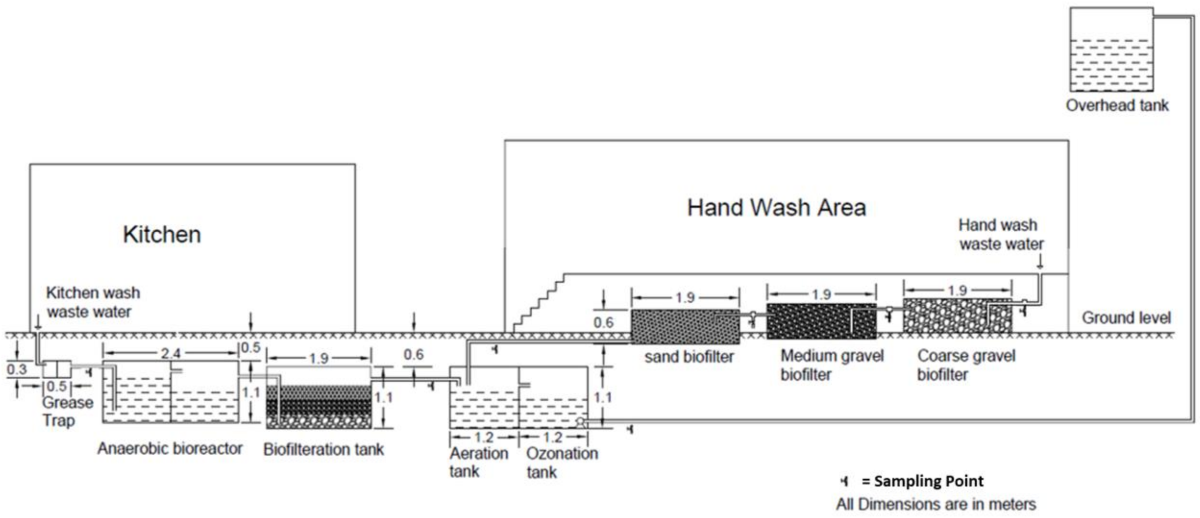

**Figure 1:** Block diagram of the greywater treatment stages for handwash greywater and kitchen wash greywater.

The HW treatment module consisted of sink bucket traps with 2 mm pore size as a pre-treatment stage before the filtration stages. Figure 2a shows a picture of the sink strainer used to separate out large food particles. Following this, three anaerobic bio-filters i.e., concrete tanks filled with decreasing particle sizes (coarse gravel (20-40 mm), medium gravel (4-20 mm) and sand (2-4 mm)), were used in the treatment train. Locally available gravel was chosen as filling material in these tanks and the tanks were closed to achieve anaerobic biofilm growth conditions. The three biofiltration tanks (with their lids open) is shown in Figure 2b through 2c. The volume of each of these filter units, their porosity and hydraulic residence times are tabulated in table 1. In the coarse and medium gravel biofilters, the GW feed pipes were brought to the bottom of the filtration tanks to achieve an upward flow during operation and to keep these filters partially flooded to facilitate biofilm growth. The system was not inoculated with any bacteria and was left to naturally acclimatize. The overflow line from the medium gravel filter was introduced to the top of the sand filter as shown in Figure 2c, wherein the water trickles down through medium gravel biofilter before exiting from the bottom of the biofilteration tank. The filtered water was then fed to the aeration tank for aeration.

A recent study had also reported that handwashing soap is the dominant ingredient in the handwash water[36]. In the handwash area the students were instructed not to use any soaps as that could potentially increase the nutrient level in the HW water. This practice was not followed in the school from January to March but was implemented from July-December.

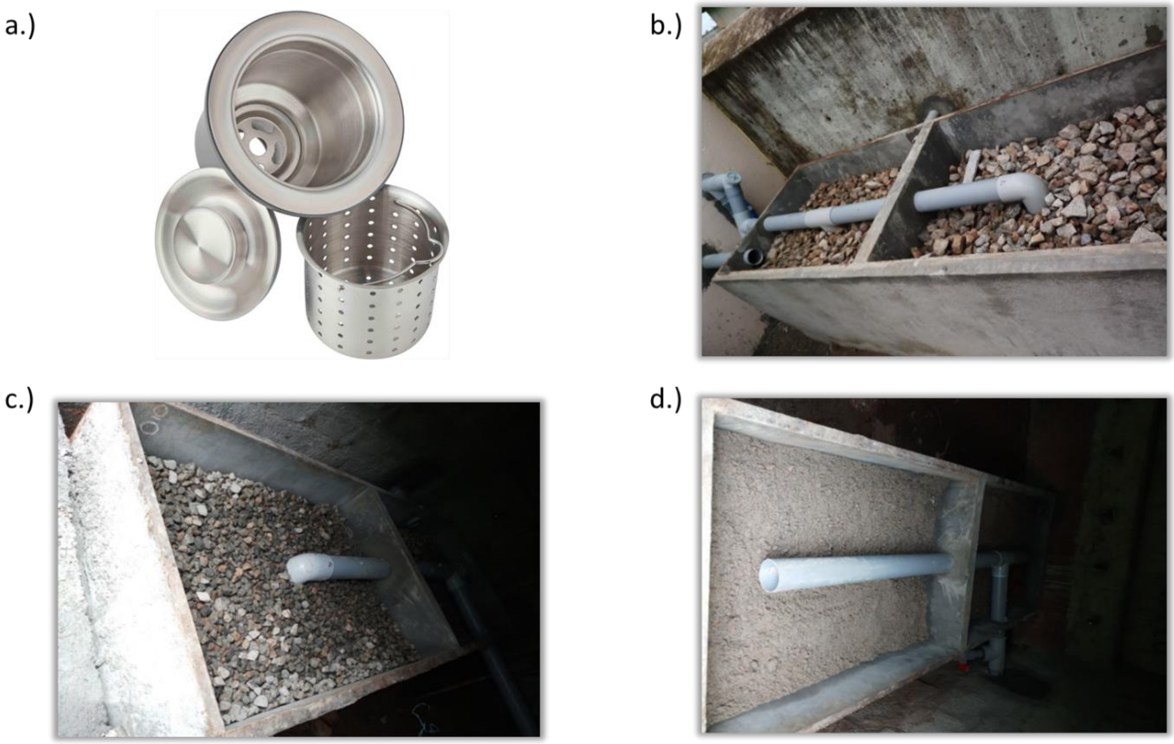

**Figure 2:** Different stages of the HW treatment train a) Sink strainers in handwash sink, b) Coarse gravel biofilter c) Medium gravel biofilter and d) Sand biofilter

The KW treatment module consisted of bar screens of 5 mm opening size and an oil and grease trap as pretreatment stages. The oil and grease trap, as shown in Figure 3a, had a detachable perforated (3 mm) basket, and a secondary chamber where oil and grease can be trapped and skimmed off. Following this, the KW wastewater was fed to the bottom of an anaerobic sludge bioreactor (AnSBR) as shown in Figure 3b. The overflow from the AnSBR was introduced to the bottom of a biofiltration chamber. The biofiltration chamber was a stratified column of coarse gravel (20-40 mm), medium gravel (4-20 mm) and sand (2-4 mm) as shown in Figure 1. The coarse gravel was used at the bottom of the biofilter whereas fine gravel was used at the top. The KW wastewater was made to flow in upward direction first through the coarse gravel, followed by medium gravel and finally through sand layers to achieve bio-filtration. The overflow line from this biofiltration tank was connected to the aeration tank as shown in Figure 1.

In the kitchen wash area Vim™ soap was used for utensil cleaning. The manufacturers claim the composition of Vim soap to be Sodium LAS, Sodium Carbonate, Neem Oil, Concentrated Lime Juice, CI 74260, CI 11680, and Water[37].

In the aeration tank, the filtered water from HW and KW was mixed and aerated using locally made diffuse aeration pipes. As shown in Figure 3c, the aeration system consisted of updraft diffusers, designed using locally sourced PVC pipelines (1 inch $dia$) perforated ($3 – 4\ mm$) at equal intervals. The aerated water entered the bottom of the ozonation tank through gravity displacement. Cold plasma powered high throughput ozonators, as shown in Figure 3d, delivering up to 10 gm/hr of ozone were used to achieve ozonation of the GW. The ozonation tank was also fitted with the updraft diffusers to achieve the proper contact of ozone with the GW. The treated GW from the ozonation tank was pumped to an overhead treated GW tank, using a solar-powered submersible water pump. The ozonators, aeration system and water pumps were powered using solar panels. The design volumes and hydraulic residence time of all these units are given in table 1.

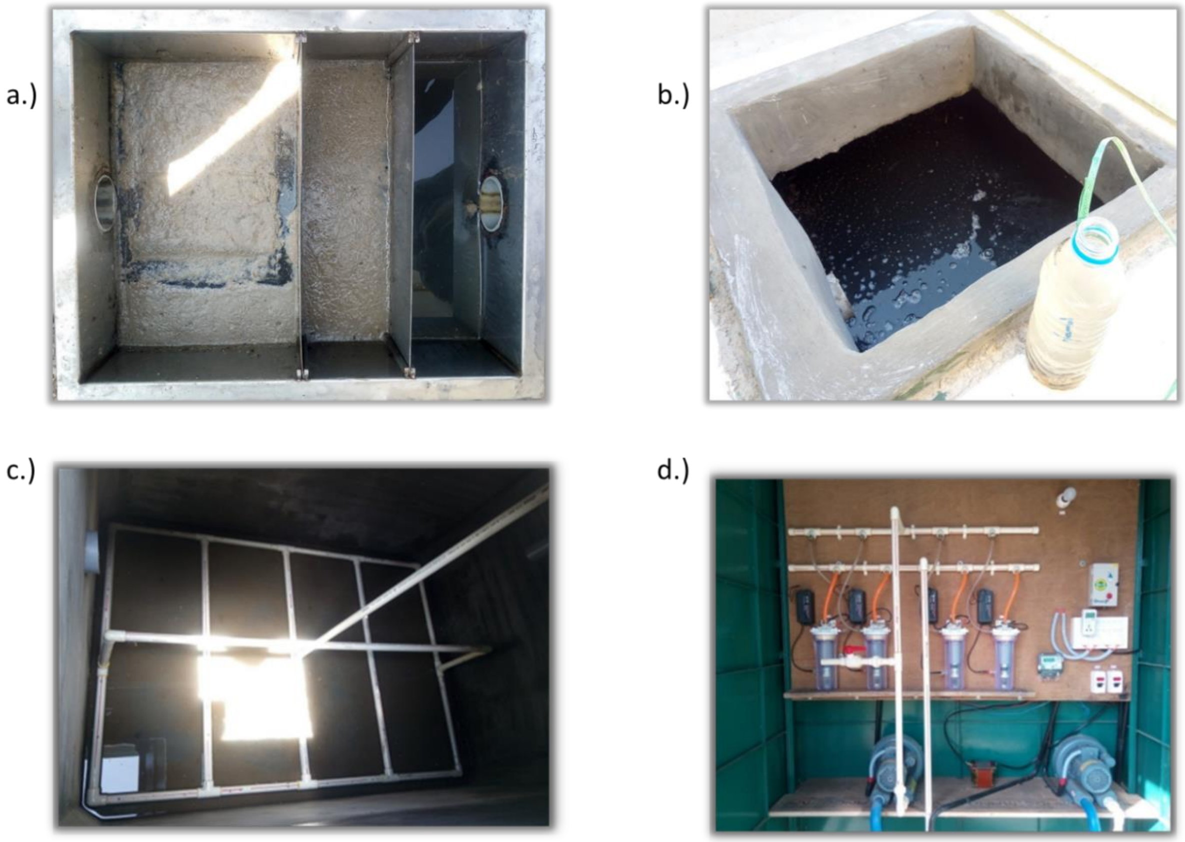

**Figure 3:** Pictures of KW treatment a) Grease trap b) Anaerobic upwelling sludge bioreactor, c) Diffuse aeration system of aeration and ozonation tank d) cold plasma ozonator

**Table 1:** Stagewise sizing and retention time

| Treatment Stages | | Total Volume (L) | Design flow rate (LPD) | Porosity (%) | Hydraulic Retention time (hours) | |
|---|---|---|---|---|---|---|
| Handwash biofilters | Coarse gravel biofilter | 1014 | 750 | 35 | 11.4 | 31.2 |
| | Medium gravel biofilter | 1014 | 750 | 33 | 10.7 | |
| | Sand biofilter | 1014 | 750 | 28 | 9.1 | |
| Kitchen wash filter | Oil and grease trap | 148 | 750 | | 4.7 | 52 |
| | Anaerobic sludge bioreactor | 1130 | 750 | | 36.2 | |
| | Stratified column biofilter | 990 | 750 | 35 | 11.1 | |
| Aeration tank | Aeration tank | 620 | 1500 | | 9.9 (1.5 h treatment time) | |
| Ozonation tank | Ozonation tank | 620 | 1500 | | 9.9 (0.5 h treatment time) | |

As shown in Table 1, the hydraulic retention time (HRT) for the HW and KW treatment modules were 31.2 h and 52 h respectively.  The HRT for the overall treatment (including the aeration and ozonation) residence time for treating the HW and KW streams were 51 h (~2 days) and 71 h (~3 days) respectively.

## 2.3 System Operation

On a typical working day, the school opens at 8:30 am and closes at 4:30 pm. The lunch (mid-day meals) was served in the afternoon between 12:30 pm and 2:00 pm, during which time most of the day's GW is generated and channeled through treatment units.

As a first operation step, the treated GW from the ozonation tank was pumped to the overhead tank daily at 9:30 am. This pumping operation took between 15 to 20 minutes. At the end of the pumping, the ozonation tank was emptied to make room for new water to be ozonated. The aeration was performed daily for 90 mins from 10 am to 11:30 am and the aerated water was allowed to settle for 30-60 mins, before receiving the fresh load, which started after lunch between 1 and 2 pm from HW sinks and between 2 and 3 pm from KW sinks. As the system was gravity fed, the HW and KW water generated in a day displaced the water present in the biofilters and AnSBR. The entry of a new batch resulted in the overflow of the aerated water from the aeration chamber into the ozonation chamber. Ozonation was performed between 3:30 pm and 4:00 pm daily. This treated GW in the ozonation tank was allowed to stay overnight before being pumped to the overhead tank the next morning.

The timings for the operation of the ozonators and aerators were optimized after quantifying the flow rates in each stage of the system daily, so as to obtain treated water at the beginning of the day and with the least energy consumption. Despite these optimizations, the end quality of water would vary significantly (within the acceptable limits of reuse) due to the high variations in the input parameters to the GW treatment system. Factors such as school attendance, the seasonal variation in the availability of greens and vegetables, guests coming to the school and cultural events in the village affected the GW quality. These external factors were responsible for the variations in the quality and quantity of GW generated, which is discussed in the results and discussion section 3.0.

### 2.4 Sampling methodology

Sampling ports were installed using valves at the end of each stage as shown in Figure 1. Water samples were collected at each of these ports in a sterilized sample collection container, fortnightly over a period of one year. These samples were analyzed for standard water quality parameters using APHA protocols[38]. Samples were analyzed for pH, total suspended solids (TSS), total dissolved solids (TDS), nitrates ($NO_3^-$), total phosphorus (TP), phosphates ($PO_4^{3-}$) , temperature (T), biological oxygen demand ($BOD_5$), turbidity, chemical oxygen demand (COD), total organic carbon (TOC) and fecal coliform counts (FC).The unit of measurement was NTU for turbidity, MPN/100 mL for FC, and ppm for all other parameters. The post-treatment water quality parameters at each stage were compared with the relevant water sewage discharge standards for recycling and reuse [39,40]. All the data were statistically analyzed using MS Excel Data Analysis tools for statistical measurements such as two-tailed t-test to verify statistical significance. All data is represented in the form mean $\pm$ standard deviation ($\mu \pm \sigma$).

The quantity of water consumed at the KW and HW areas were also measured on a monthly frequency to assess the containment loading rates and evaluate the removal efficiencies, due to the separate treatment of these two GW streams.

### 2.5 Operation and maintenance

One of the major attractions that the system offers is its ease of operation and maintenance. The system has no major machinery requiring skilled labor for operation. The maintenance of the system is only involves cleaning tanks and filters biannually. The detachable perforated basket in the grease trap is washed on a biweekly basis. At present, the system is operated by the school staff after a training and transition period of one year.

The system, therefore, has the potential to be replicated as well as scaled up. Such decentralized plants can also be conveniently built-in urban settings such as apartments, hospitals, and educational institutions, depending on local climatic conditions, population density and land availability.

## 2.6 Calculations

The removal efficiencies (RE) for the parameters of turbidity, TSS, $BOD_5$, COD, $NO_3^-$ TP, TOC and FC were evaluated for each of the water treatment steps. The removal efficiency of the overall treatment was measured using the percentage reduction in the concentration from the samples collected pre and post-treatment, which is represented by equation 1[41].

$$\text{Removal Efficiency (RE)} = 100 \times \frac{C_i - C_o}{C_i} \qquad (1),$$

where $C_i$ and $C_o$ are the concentrations of the parameters at the influent and effluent samples respectively.

As the aeration and ozonation stages had two inlets with variable flow rates, removal efficiency calculations were measured by load, and not concentration. Load ($L_p$) of parameter p was measured using $L_p = C_p \times V$, where $C_p$ and V is the concentration of parameter p and volume of the GW.

Removal efficiency of the aeration and ozonation stages for parameter p was measured using the equation:

$$RE_p = \frac{(Load_{HW}+Load_{KW})-(Load_{out})}{Load_{HW}+Load_{KW}} \times 100 = 100 \times \frac{(C_{p\,HW} \times V_{HW} + C_{p\,KW} \times V_{KW}) - C_{p\,out} \times V_{out}}{C_{p\,HW} \times V_{HW} + C_{p\,KW} \times V_{KW}} \qquad (2),$$

Where $C_{p\ HW}$, $C_{p\ KW}$, and $C_{p\ out}$ are the concentration of parameter p at the handwash filter outlet, kitchen wash filter outlet and ozonation outlet respectively, $V_{HW}$, $V_{KW}$, and $V_{out}$ are the volume of GW at the handwash filter outlet, kitchen wash filter outlet and ozonation outlet respectively.

The organic loading rates (OLR) were calculated using the following equation:

$$\mathrm{OLR} = \mathrm{C_{COD}} \times \frac{\mathrm{Q_{in}}}{V_{tr}} = \frac{C_{COD}}{HRT_{tr}} \qquad (3),$$

Where OLR is the organic loading rate in g COD/($m^3$·day), $C_{COD}$ is the COD concentration in the input (g COD/$m^3$), $Q_{in}$ is the volumetric flow rate of the wastewater ($m^3$/day), and $V_{tr}$ is the volume of the treatment component. The ratio of the volume of the treatment component and the inflow rate is equal to the hydraulic retention time ($HRT$).

# 3 Results and Discussions

## 3.1 Baseline Study Results

The baseline water quality was measured at the inlet of the school and also at the outlet of the kitchen sink and handwash sink. The baseline study for the GW was done by sampling the water coming out of the kitchen wash (KW) and handwash (HW) areas before mixing, at three different times daily for four days. The average values of the physicochemical and biological parameters obtained in this study are presented in table 2 along with previously reported values for GW treatment and reuse systems from across the globe.

**Table 2:** Baseline greywater characteristics reported in the literature and the data at handwash (HW) and kitchen wash (KW) outlets obtained in this study.

| S.No | Reference | Location | Greywater Characteristics | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Turbidity (NTU) | TSS (ppm) | $BOD_5$ (ppm) | COD (ppm) | Nitrate (ppm) | FC | TP |
| 1 | [21] | Egypt | | 105 | 298.6 | 395 | | | 10.5 |
| 2 | [22] | Saudi Arabia | 103 | 79 | 119 | 219 | 0 | | 9.8 |
| 3 HW | [23] | Greece | | 61 | | 335 | | | $0.7(PO_4^-)$ |
| 4 KW | [23] | Greece | | 299 | | 775 | | | $0.4(PO_4^-)$ |
| 5 | [24] | Brazil | 40.4 | 76 | 93 | 170 | 33 | | |
| 6 | [25] | Costa Rica | 96 | | 167 | | | $1.5 \pm 4.6 \times 10^8$ | $16 \pm 15\ (PO_4^-)$ |
| 7 | [26] | Jordan | | 845 | 1056 | 2568 | | $7 \times 10^5$ | 18.25 |
| 8 | [27] | Estonia | | 158 | 442 ($BOD_7$) | 695 | 0.1 | | 7.1 |
| 9 | [28] | Uganda | | 2828 | 1395 | 6563 | 12 | $8.72 \times 10^7$ | 6.2 |
| 10 HW sinks [29] | [29] | Brazil | 35.8 | | 56 | 145.8 | | $1.8 \times 10^5$ | |
| 11 | [30] | India | 29.7 | 14.8 | 78 | 264 | 2.4 | $3.5 \times 10^4$ | |
| 12 HW This Study | | India | 196 ± 112 | 351 ± 223 | 344 ± 272 | 643 ± 387 | 34 ± 6 | $2.35 \times 10^8$ | 1.03 ± 0.68 |
| 13 KW This Study | | India | 225 ± 118 | 619 ± 237 | 445 ± 165 | 553 ± 267 | 40 ± 6 | $2.26 \times 10^8$ | 4.53 ± 2.01 |

Compared to the quality of inlet water being supplied to the school (Turbidity=0.17, TSS=13, COD=23 and $NO_3^-$=34) the water at the GW outlet showed much higher values of Turbidity, TSS, COD, and FC as expected as shown in table 2.

When the baseline greywater characteristics obtained in this study are compared with the previously reported values, the TSS, $BOD_5$ and COD values fall within the range of the reported values. These values are higher than most values reported but not as high as the values reported by Halalseh et al and Katukiza et al for the Jordanian and Ugandan scenarios[26,28]. Halalseh et al had reported that the high values obtained in their study was due to the very low per capita water consumption in Jordan[26]. The turbidity values are higher than the typically reported values[22,24]. Nitrate values obtained are comparable to values reported by Couto et al. in the Brazilian scenario[24]. It should be noted that the $NO_3^-$ in the raw inlet water supplied to the school itself was high at 34 ppm. Mandal et al. also conducted a study in India but in an urban scenario. The significantly higher values of all the aforementioned parameters in this study when compared to the values reported by Mandal et al indicate a wide disparity in the GW characteristics between the rural and urban areas within the same country[30].

As can be seen from Table 2, there were variations in the quality of the wastewater generated in the school, depicted by the standard deviation in mean values. These variations were due to several day-to-day variations in school attendance and other factors such as the seasonal variation in the availability of greens and vegetables, guests coming to the school, and cultural events in the village.

The water consumption of the school was monitored three times daily for three months as part of the baseline study at three different points. The first point was at the inlet of the school measuring the overall water consumption of the school. The subsequent two points of measurements were before the HW and KW areas measuring the respective consumption in each of these areas. This data was used to calculate the loading factor and reduction of freshwater consumption which is discussed in section 3.6.

### 3.2 Pretreatment of HW and KW wastewater using coarse strainers and grease trap

Prior to the slow sand bio-filtration stages, both the KW and HW were directed through separate pretreatment stages. The pretreatment stage was used to alleviate the stress caused by large food particles on the downstream treatment units. Baseline studies clearly indicated the need for installing traps to remove large chunks of food particles which would otherwise potentially clog up the downstream equipment. Also, the KW sink generated GW having high levels of oil and grease. To address this, pretreatment stages were installed.

The HW pretreatment was achieved using particle trapping sink strainers with 2 mm pore diameter as shown in Figure 2a. These strainers would screen out the large food particles and help in reducing the TSS and turbidity of the GW. The removal efficiency of this stage for turbidity and TSS was evaluated by comparing the baseline GW and the post pretreatment GW. Removal efficiencies (RE) of 88% for turbidity and 75% for TSS, was achieved by the pretreatment strainers as shown in table 3.

The KW treatment module had a grease trapper for pretreatment. The grease trapper was intended to reduce the TSS and turbidity of the GW by trapping the oil and grease present in the KW wastewater. Table 3 shows the turbidity and TSS of the GW from KW sink before and after pretreatment. The KW pretreatment using grease trapper achieved RE of 65% and 89% for turbidity and TSS respectively as shown in table 3. The TSS levels at the outlets of both the pretreatment stages averaged around 80 ppm.

**Table 3:** Turbidity and TSS removal efficiency of pretreatment stages

| | HW before pre-treatment | HW after pre-treatment | Avg. Removal Efficiency (%) | KW before pre-treatment | KW after pre-treatment | Avg. Removal Efficiency (%) |
|---|---|---|---|---|---|---|
| Turb (NTU) | $196 \pm 112$ | $24 \pm 12$ | 88 | $225 \pm 118$ | $78 \pm 55$ | 65 |
| TSS (ppm) | $351 \pm 223$ | $88 \pm 48$ | 75 | $619 \pm 237$ | $73 \pm 30$ | 89 |

### 3.3 Performance of biofilters in treating HW greywater

The HW filtration consisted of three separate anaerobic biofilm slow sand filtration chambers. The average organic loading rates in HW filtration system was calculated using equation 3 and was found to be $\sim$109 g $\mathrm{COD/m^3}$ day.

Figure 4 shows the load and removal efficiency of the HW filtration stages over the operational period (the school was not operational during April-June due to summer vacation). Figure 4a and Figure 4b shows that the input $\mathrm{NO_3^-}$ load was between 12 ± 2 g for most of the months and TP load was between 0.75 ± 0.25 g. The $\mathrm{NO_3^-}$ removal fluctuated between 60% and 95% and averaged around 79%. The removal efficiency of TP fluctuated between the months, but this did noteffect the overall performance as TP was low ($\sim$1 ppm) in the GW from HW area, thereby not impacting its reuse capacity. From Figure 4c and 4d it can be seen that, the $BOD_5$ and COD load for the system were between 70 ± 10 g and 140 ± 20 g respectively. The $BOD_5$ and COD removal efficiencies were consistent throughout the operational period at around 92% and 83% respectively, despite breaks in the operation due to the summer vacation. This indicates that the system is able to perform even with breaks in feed to the biofiltration units.

Figure 4c and 4d illustrate the consistent removal efficienct (RE) of $BOD_5$ and COD throughout the operational period except in November. The low RE of COD in November can be attributed to the relatively lower input COD load on that particular month. The high removal efficiency for the $BOD_5$ and COD achieved by the HW filtration stages bring the GW within the treated water reuse norms for $BOD_5$ and COD, details of which are discussed further in section 3.6.

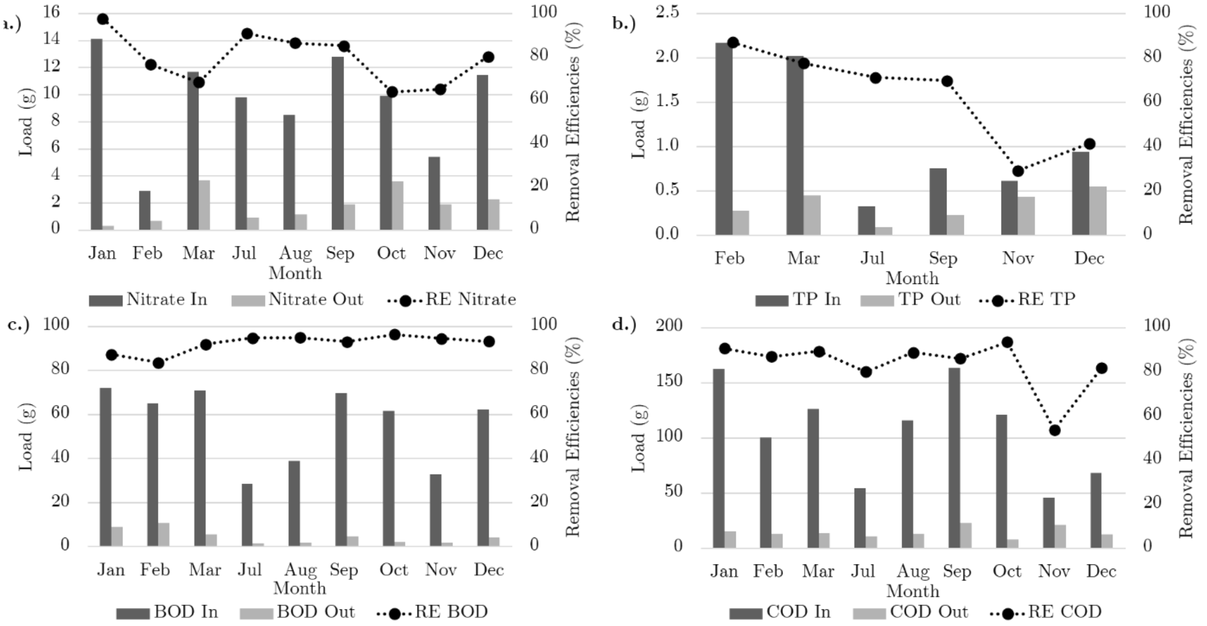

**Figure 4:** Load and removal efficiencies of the HW filtration stages for a) $NO_3^-$, b) TP, c) $BOD_5$ and d) COD over the operational period.

Figure 5a and 5b, shows the picture of the coarse gravel taken during installation and one month after the commencement of the plant operation respectively. From Figure 5b, the biofilm layer formation after one month of the commencement of system operation is evident on the filter media. The formation of the biofilm layer has been reported to potentially enhance the removal efficiencies through possible several pathways which include biosorption, biological degradation of soluble organics and also reduces odor and color[42]. The microbial communities thriving on the biofilm are known to be responsible for the breakdown of different nutrients, such as phosphorous and nitrogen-containing compounds, carbonaceous materials as well as the removal of trapped pathogens from the wastewater[43,44]. The high removal efficiency observed in this study can be attributed to the presence of these biofilms. The reduction in the TP values may have been influenced by the students not using handwash soaps after the month of July in the handwash areas.

**Figure 5:** Picture of coarse gravel during installation(left/a) and one month after commencement of system operations(right/b).

### 3.4 Performance of AnSBR and biofilters in treating KW greywater

The average organic loading rates in the KW module after the pretreatment were calculated using equation 3 and averaged around 179 g $\mathrm{COD/m^3}$ day, which was about 64% higher than the HW greywater. As expected, the average organic loading rates from the kitchen sink were higher than that from the handwash sinks.

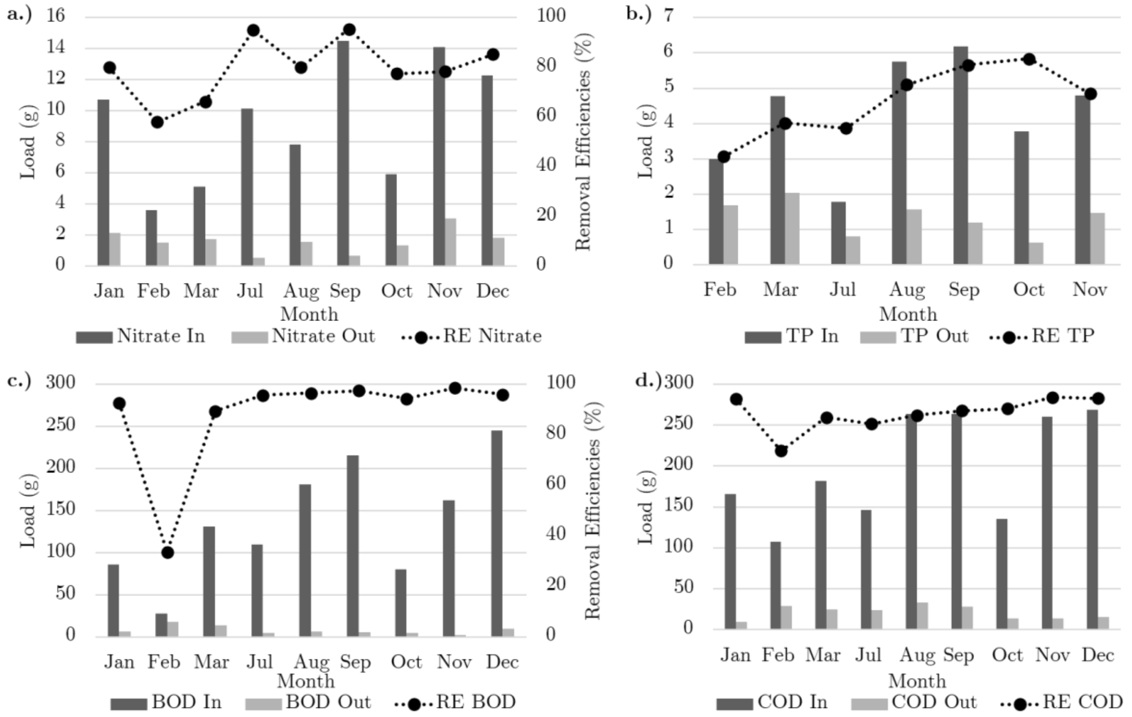

**Figure 6:** Load and removal efficiencies of the KW filtration stages for a) $NO_3^-$, b) TP, c) $BOD_5$ and d) COD over the operational period.

Figure 6 shows the load and removal efficiency of the KW module consisting of AnSBR and filtration stages over the operational period. As shown in Figure 6a and 6b, the $NO_3^-$ and TP load from KW wastewater was between 12 ± 2 g and 4.5 ± 2 g respectively. Although the $NO_3^-$load in the KW stream, was similar to that of HW stream, the TP load was almost double. This high load of TP is attributed to the oil coming from washing of cooking utensils and the cleaning products used in the kitchen. The RE of $NO_3^-$ fluctuated between 80% and 95% and averaged to be around 88%. The RE of TP fluctuated between 40% and 80% averaging around 69% and it is believed that the resuspension of biofilms into the water is the reason for such fluctuations. Figure 6c and 6d illustrate that the $BOD_5$ and COD of the KW stream was higher than the HW stream (Figure 5c and 5d). This higher load is again believed to be coming from the oil films present on the utensils and washing products used in the kitchen. As can be seen from Figure 6c and 6d, the $BOD_5$ and COD RE stayed consistent throughout the operational period (except February) at around 80% and 69% respectively. The exception in RE of $BOD_5$ for February can be attributed to the lower BOD loads on that month. This trend is similar to that observed in the HW filtration.

The RE of $BOD_5$ and COD of the KW module was relatively lower than that of the HW module. The AnSBR of the KW module had an HRT of 33 h, and it was noticed that, even after 12 months of operations, there was very little sludge present in the AnSBR.

Typically in the enhanced biological phosphate removal systems COD uptake and P-release occurs in the anaerobic conditions[45]. The exact mechanism of phosphorus (P) removal is yet to be fully understood in an anaerobic system. Past studies have also reported this observation and hypothesized two possible explanations. Wang et al had reported 50-70% phosphate uptake efficiencies in their study and found a correlation between anaerobic uptake of acetate and phosphates[45]. Keating et al also observed phosphate removal in the anaerobic digestion of wastewater treatment and hypothesized the removal mechanism to be biological in nature, mediated by the biofilms in the reactor[46]. The formation of biofilm was observed in the HW stages of the treatment but could not be monitored in the KW stages due to the filtration units being below the ground level. The odor in the KW water obtained after filtration indicates the presence of anaerobic microorganisms in the KW filtration stages, and biofilm formation is expected in the KW filter. These indicate that the biofilm or anaerobic microorganism in the KW filtration stage is responsible for the TP reduction similar to what was reported by Keating et al[46].

The KW filtration stages had a lower HRT than the HW filtration stages. This was designed as the AnSBR was intended to be the main component in removing $BOD_5$ and COD. The low sludge level in the AnSBR coupled with lower overall surface area and HRT in the stratified bio-filtration units are believed to be the reason for relatively lower RE for $BOD_5$ and COD.

### 3.4 Performance of aeration and ozonation modules

The filtered water obtained at the end of the filtration stages of both KW and HW systems looked clear as shown in Figure 7, but was not free of odor. Furthermore, the FC of these samples at the end of the treatment stages was over 1000 MPN/100 mL which exceeds the Karnataka State Pollution Control Board (KSPCB) treated sewage discharge standards [39,40]. This standard mentions that it applies to recycling and reuse of treated effluent involving human contact[39]. The water obtained at the end of KW filtration did not meet the KSPCB effluent reuse standard norms for $BOD_5$ and COD, which also needed to be addressed. Aeration and ozonation were performed following filtration to resolve these issues. Ozonation enables the removal of odor, color, micropollutants [47] and enhances the disinfection capabilities offered by the treatment plant. The average organic loading rates for the aeration system was calculated using equation 3 and averaged around 77 $\text{g COD/m}^3$ day.

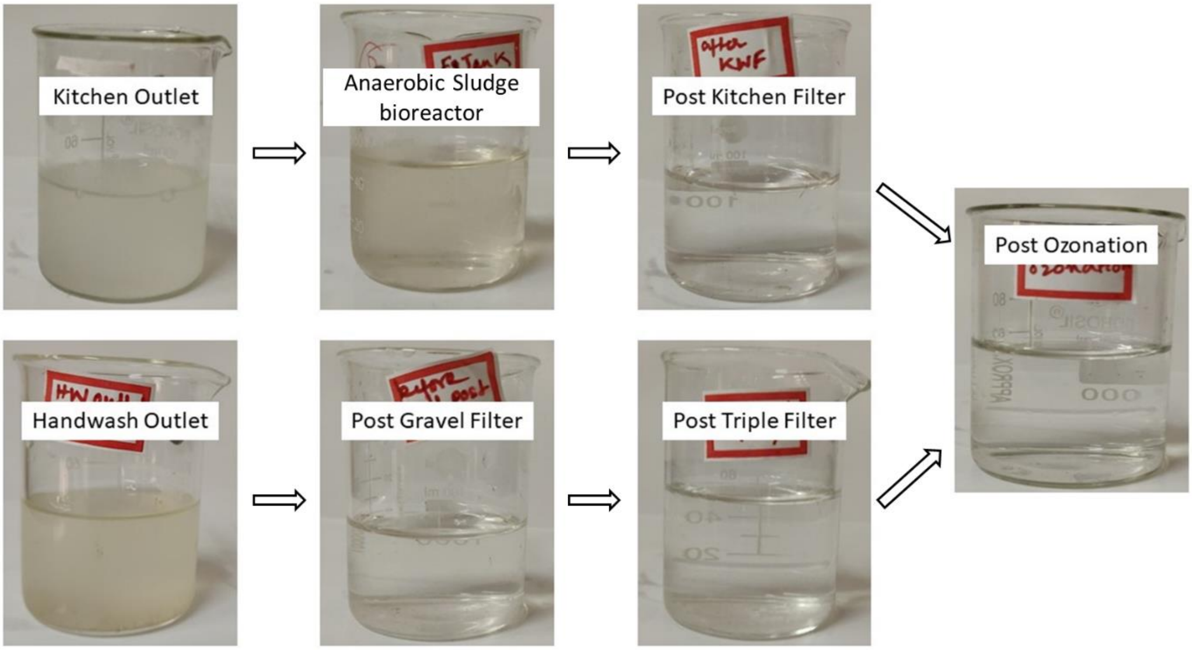

**Figure 7:** Visual appearance of water at different treatment stages

Ozone generated from on-site plasma sources was used for the final disinfection stage. Despite the higher economic cost of plasma-based ozonation compared to chlorination, plasma-based ozonation results in fewer health impacts relative to chlorination[48,49]. Ozone is known, to be superior to chlorine in destroying viruses and bacteria, with contact time of 10 to 30 minutes, has no harmful residues, and prevents the biofilm growth and regrowth of microorganisms in wastewater streams [49]. As the treatment module was located in a remote area, a decentralized approach for the disinfection process using ozonation was preferred over chlorination as it would reduce the risks associated with handling and shipping of chlorine[49]. Furthermore, ozonation is also known to elevate the DO concentration as oxygen is the byproduct of ozone degradation[49]. This reduces the required aeration time for the treatment process to achieve safe DO levels.

The ozonators were tailormade specifically for the purpose of WW treatment as part of this work. Rao et al had reported the design and performance of the same ozonator at lower flow rates and ozone outputs (20 LPM flow rater for 1.2 g $h^{-1}$ ozone production) for decentralized GW applications[50]. A 69% reduction in COD was reported upon 30 min of ozonation [50]. For this study, and based on the results reported by Rao et al, the ozonator design was modified and optimized to operate at the higher flow air rates (100 LPM) and produce higher ozone output (4.5 g $h^{-1}$).The ozonator did not require pure oxygen as a feed gas like most of the commercially available ozonators but worked with ambient air as the feed gas. This was more practical as the supply of oxygen cylinders to a rural area is not economically feasible. Furthermore, oxygen cylinders are a fire and explosion hazard in a school, which requires skilled technical labor for operation and maintenance. To achieve a decentralized system the ozonator was designed to be easy to operate and maintain, requiring no external materials after post-installation. This ozonator was fed air using a compressor, bypassing the need of compressed oxygen cylinders[50]. Four ozonators were placed in parallel as shown in Figure 3 d and operated only for 30 mins daily to achieve the required effluent sewage and reuse standards for the treated GW.

The cost estimation for the disinfection of wastewater using chlorine, ozone and UV varies based on the volume of water treated daily[51]. The cost of treating 1 $kL$ of water using chlorine, ozone, hypochlorite and UV are in the ranges of 0.02-4 \$, 0.18-11.7 \$, 0.03-4 \$ and 0.02-8 \$ respectively [49,51–54].

Figure 8 shows the load and removal efficiencies of the aeration and ozonation stages for turbidity, TSS, $BOD_5$ and COD over the operational period. The turbidity removal efficiency was consistently between 70% and 88% and averages around 83%. The removal efficiency of TSS, $BOD_5$ and COD showed variations but averaged around 80, 58 and 49% respectively. The removal efficiency of $BOD_5$ and COD may seem low, but it must be noted that this is an enhancement to the high removal efficiencies achieved already by the previous stages.

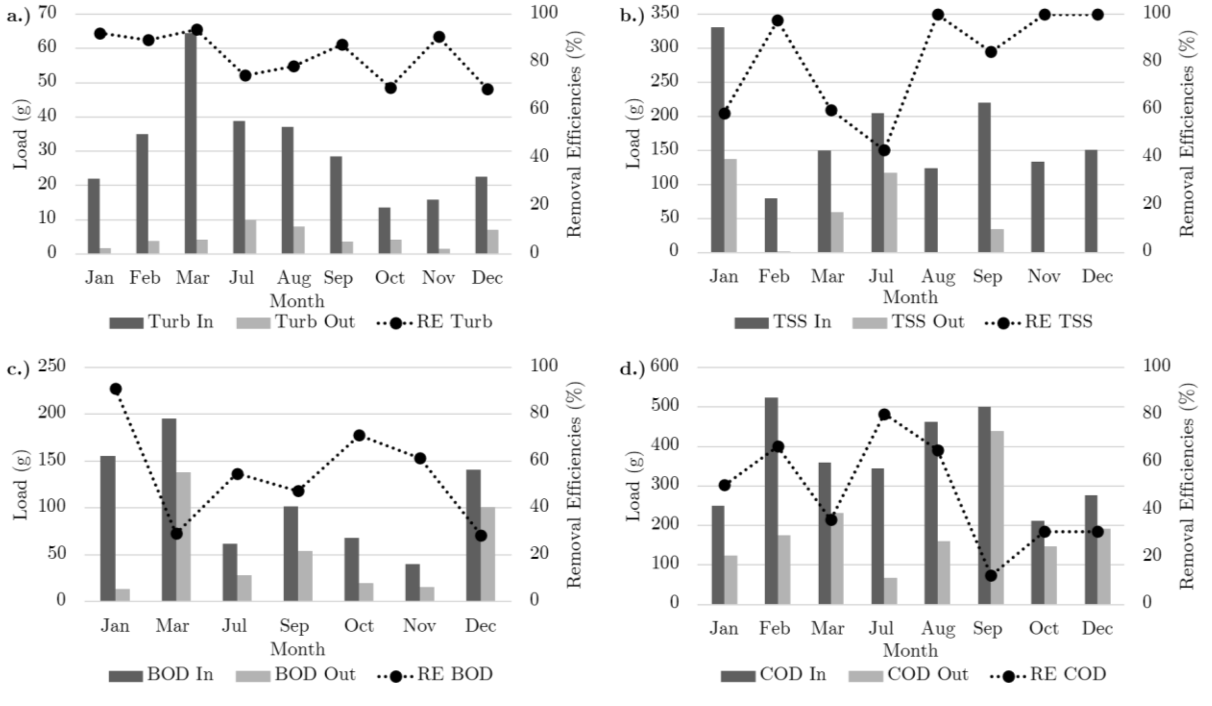

**Figure 8:** Load and removal efficiencies of the aeration and ozonation for a) turbidity, b) TSS, c) $BOD_5$ and d) COD over the operational period.

The FC present in water collected from different sampling points were measured. Table 4 shows the log lower reduction value (LRV) and log higher reduction value (HRV) at different stages of treatment.

**Table 4:** Log kill of coliform at each treatment stage

| Stage | Log LRV | Log HRV | Avg. Log Reduction |
|---|---|---|---|
| HW Bio-filtration | 1.22 | 5.25 | 3.37 |
| KW Bio-filtration | 1.47 | 3.86 | 2.96 |
| Ozonation | 0.59 | 4.93 | 1.97 |

The filtration shows an average log reduction of 3.37 and 2.96 in the HW and KW filters. The difference in the LRV and HRV can be attributed to the difference in the FC concentration in the source water.

The ozonator enhanced the disinfection capabilities by reducing the FC by 2 log to the filter-treated water. The water obtained post-ozonation shows very low coliform values 28 MPN/100 ml) and can be safely utilized for non-potable domestic purposes. The ozone-treated water at the outlet was free of odor and color. Even after 12 months of use, there was no evidence of any biofilm on the downstream pipes and tanks of the treated GW distribution system. Also, there was no evidence of any malodor in the treated GW post ozonation.

### 3.5 Overall system Performance

The water quality parameters at different stages of treatment are shown in table 5, alongside the treated sewage discharge standards of the KSPCB. It was observed that the pretreatment stages are effective for the removal of turbidity and TSS without which, the slow sand bio-filters would have clogged leading to the requirement for frequent maintenance and increased associated costs. The RE of $BOD_5$ in the HW pretreatment was around 50%, which was only

10% in the KW pretreatment. This could be attributed to the high amount of food waste that was discharged into the handwash area as shown in Figure 4. This solid food waste was the main constituent responsible for the $BOD_5$ of the HW stream. In the KW stream, $BOD_5$ is attributed to several constituents of not all of which were removed by the pretreatment.

The filtration stages of both KW and HW streams reduce the Turbidity and TSS but do not bring them within the sewage discharge and reuse standards. The $BOD_5$ and COD removal of the HW filtration achieves permissible limits. The KW filtration does not bring the $BOD_5$ and COD to permissible limits due to poor performance of the AnSBR, higher OLR and lower HRT in the KW bio-filters. The FC in both the KW and HW streams at the filtration outlet was much higher than the sewage discharge and reuse standards. The ozonation and aeration stages address these parameters and bring them well within the sewage discharge and reuse standards. It is important to note that the ozonation stage increases the $NO_3^-$ in the GW, but this range still falls within the sewage discharge and reuse standards. Rahmadi et al. [42] had reported oxidation of nitrite and ammonia to $NO_3^-$ leading to an increase in $NO_3^-$ upon oxidation. The increase in the $NO_3^-$ observed in this study could be due to the oxidation of the other nitrogen species as the overall TN was not significantly affected by the ozonation stage (Refer to Supplementary Material).

**Table 5:** Concentrations of different parameters at different stages of treatment.

| **Parameter** | **Hand wash GW baseline** | **Hand wash GW after pre-treatment** | **Hand wash GW after triple filtration** | **Kitchen wash GW** | **Kitchen wash GW after pre-treatment** | **Kitchen wash GW after anaerobic tank and updraft filtration** | **GW post aeration and ozonation (end-use)** | **KSPCB sewage discharge and reuse Standards** *[39,40]* |
|---|---|---|---|---|---|---|---|---|
| Turbidity (NTU) | 196 ± 112 | 24 ± 12 | 4.32 ± 3.84 | 225 ± 118 | 78 ± 55 | 14 ± 12 | 0.8 ± 0.4 | |
| TSS (mg/L) | 341±223 | 88±48 | 30±13.2 | 619±237 | 73±30 | 24±15 | 9 ± 3.1 | 20 |
| Nitrate (mg/L) | 34 ± 6 | 26 ± 14 | 8.58 ± 6.5 | 40 ± 6 | 28 ± 17 | 9.9 ± 3.4 | 12.4 ± 11.1 | |
| BOD$_5$ (mg/L) | 344±273 | 165±72 | 13 ± 6 | 445±165 | 402±178 | 31±16 | 9 ± 5 | 30 |
| COD (mg/L) | 633 ± 383 | 328 ± 137 | 48 ± 38 | 533 ± 267 | 497 ± 225 | 74.3 ± 23 | 27 ± 16 | 50 |
| TP (mg/L) | 1.03 ± 0.68 | | 0.46 ± 0.31 | 4.53 ± 2.01 | | 1.40 ± 0.62 | 0.46 ± 0.25 | |
| FC (MPN/100 mL) | $2.35 \times 10^8$ | $7.2 \times 10^6$ | $3.1 \times 10^3$ | $2.26 \times 10^8$ | $2.8 \times 10^6$ | $3 \times 10^3$ | 28 | 100 |

Figure 9 shows the loads and removal efficiency of the overall treatment system over the operational period. From Figure 10c and 10d, it can be seen that the RE of BOD$_5$ and COD is consistent across filtration stages before averaging around 98% and 96% respectively. The RE of NO$_3^-$ varies between 35 and 80% and averages around 66%. The RE of TP was variable but averaged aproximately 73%.

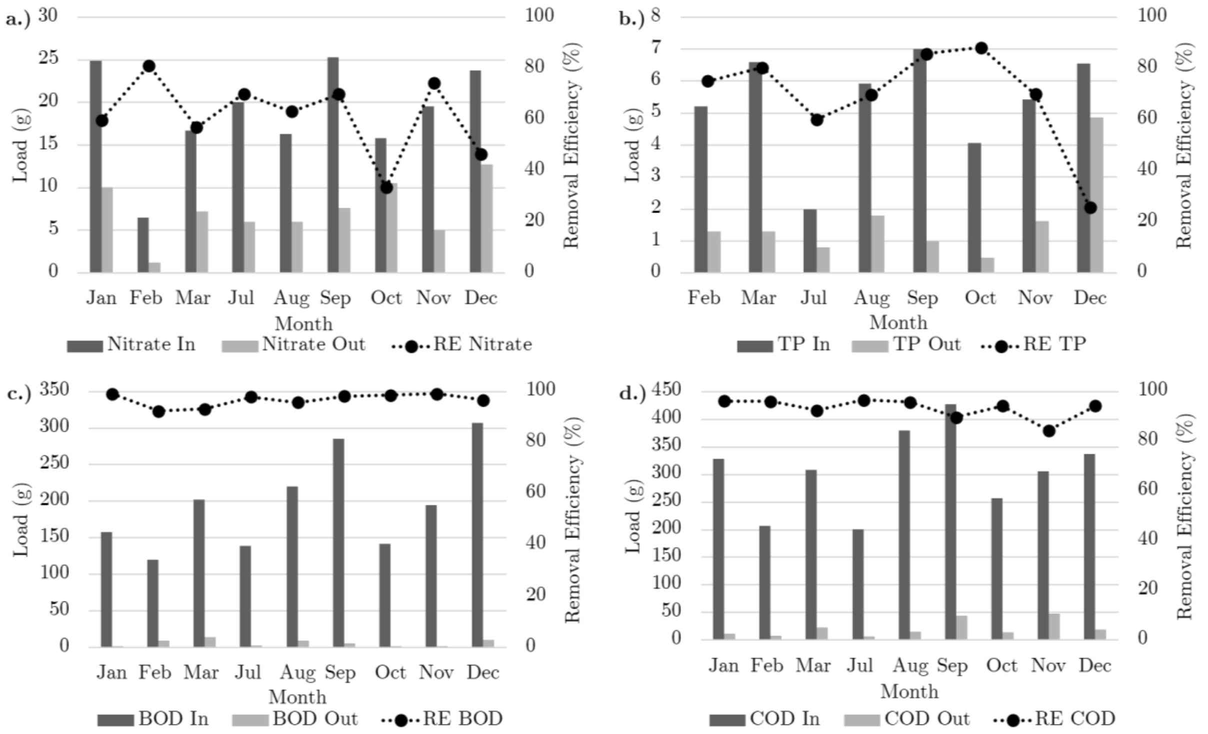

**Figure 9:** Load and removal efficiencies of the overall treatment for a) nitrate, b) TP, c) $BOD_5$ and d) COD over the operational period.

Though there are variations in the $NO_3^-$ removal over the different months it is important to note that even the untreated streams of HW and KW had $NO_3^-$ which were within the permissible limits. The overall treatment system showed RE of 99%, 98%, 66%, 73%, 98%, 96% and >99.99% in turbidity, TSS, $NO_3^-$, TP, $BOD_5$, COD and FC respectively. The relatively low removal of $NO_3^-$ when compared to the other components can be attributed to the low $NO_3^-$ concentrations in KW and HW streams.

### 3.6 Treated water reuse

An average around 667 L of water was treated daily. All of the treated GW was redirected to the toilets for flushing. This corresponds to an annual water saving of 180 kL assuming 270 working days in a year. Figure 10 shows the treated water generated from HW and KW facilities, individually.. The average water consumption in the toilet blocks adds up to be around 754 L daily. Treated GW was utilized and accounted for 85% of the total water consumption in the toilet block. It has the scope to be also be used for other non-potable purposes.

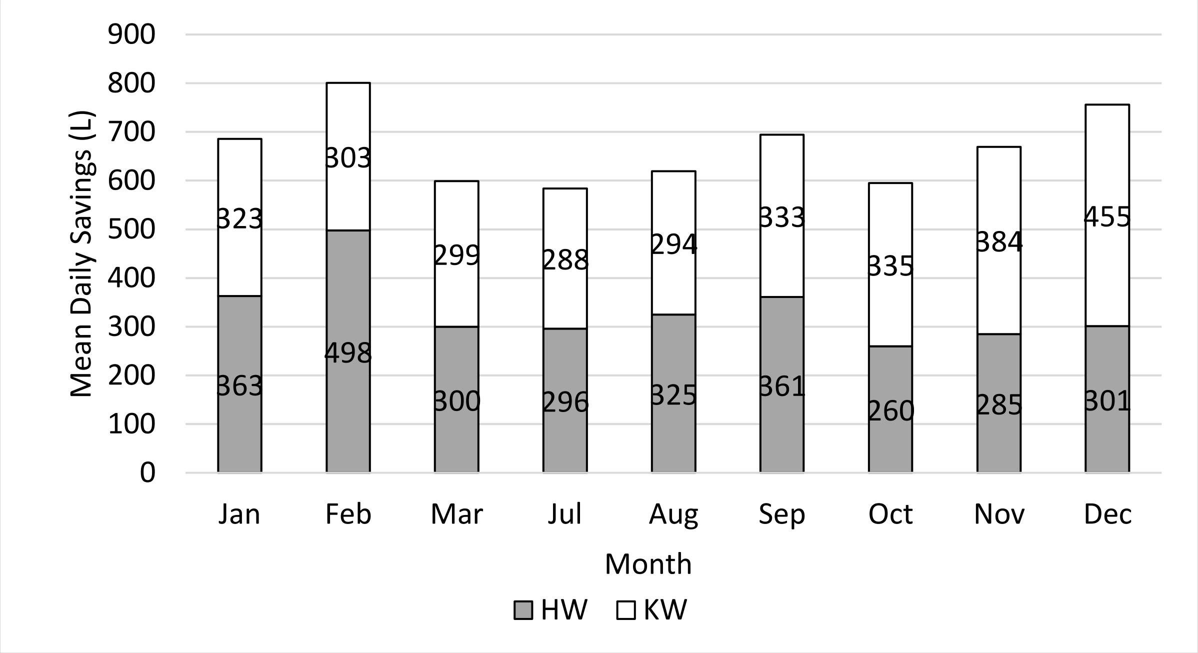

**Fig 10: Quantity of treated water from the two sources**

### 3.8 Performance of the system compared to other reported systems

The system performance was compared with values reported in the literature from field and laboratory studies conducted elsewhere for GW treatment and reuse, owing to a lack of published reports pertaining to the rural Indian context.

Table 7 provides a summary of the previously reported RE values obtained for different parameters upon GW treatment for reuse using different technologies and compares it with this study.

**Table 7:** Summary of reported wastewater treatment technologies and their performances.

| S.No | Technology Utilized | Removal Efficiencies (%) | | | | | | $\text{Log}^{+}$ |
|---|---|---|---|---|---|---|---|---|
| | | Turbidity | TSS | $BOD_5$ | COD | $NO_3^-$ | TP | FC |
| 1 [21] | Sedimentation followed by aeration along with addition of effective microorganisms | | 92.4 | 91.1 | 79.9 | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2 [22] | Rotating biological contractor followed by sedimentation and UV disinfection | | 92.8 | 95.5 | 219 | 58.6<br>(TKN) | | |
| 3 HW [23] | Coagulation with $Al_2(SO_4)_3$ followed by sand filtration and granular activated carbon adsorbtion | | 97 | | 96 | | | |
| 4 [24] | Anaerobic filtration (fiberglass) followed by UV disinfection | 88 | 77 | 73 | 72 | 60 | | |
| 5 [25] | Two reedbeds in series followed by a pond and soakage area | 97.9 | | 98.8 | | | 80 | >5 log |
| 6 [27] | Three vertical flow wells followed by a recirculation well and a horizontal filter (Filtralite® filter system) | | | 91<br>($BOD_7$) | 85 | 51<br>(TN) | 42 | |
| 7 [27] | Three vertical flow wells followed by a recirculation well and a horizontal filter (Oil shale ash filter system) | | | 85 | 80 | 46<br>(TN) | 89 | |
| 8 [28] | Sedimentation followed by two vertical flow filtration systems with crushed lava rock as filter media | | 90-94 | | 90-94 | 59.5<br>(TKN) | | >3 log |
| 9 HW [29] | Slow sand filtration followed by granular activated carbon | 61 | | 56 | 56 | | | 1.7 log |
| 10 HW [29] | Slate waste filtration followed by granular activated carbon | 66 | | 51 | 60 | | | 1.8 log |
| 11 [30] | Coarse filtration followed by equalization and secondary filtration and step aeration | 70 | 28 | 80 | 65 | 25 | 18 | 2 log |
| 12 [31] | Constructed wetland-microbial fuel cells followed by sand biofiltration and granular activated carbon filter. | | | | 99 | 63 | 75 | 4 log |
| 13 This Study | Pre-treatment followed by filtration, aeration and ozone disinfection | 99 | 98 | 98 | 96 | 66 | | 5-8 log |

+ Log reduction in removal efficiencies are shown for FC, as most of the RE %>99.

From table 7 it can be inferred that the GW treatment and reuse system installed at Berambadi government primary school shows RE which is comparable or better than the reported RE values from earlier studies. This indicates that the system installed is performing better than other existing systems in place in different parts of the world in terms of RE. The high RE obtained can be attributed to the integration of different technologies into the system. The RE values obtained in this study have been consistent for almost one year signifying the robustness of this system.

Hydraulic retention time is known to influence the RE values of any given GW treatment system[55]. Detailed analysis on the impact of HRT on the RE of this system has not been performed. As the greywater characteristics at the input described in table 2 was at the higher range, the effective treatment required a multistage process involving pre-treatment, settling cum filtration, followed by aeration and ozonation. If the GW did not contain high FC values, then there would be no need for ozonation. If the GW was devoid of the KW stream, the implementation of grease trap would not have been required. As this was a rural scenario, space was not a major constraint and a gravity-driven flow was achievable for this system. This may not be possible in the urban context as space constraints may force the system to be underground. There is no fixed system that is optimal for all GW treatment and reuse scenarios. The characteristics of GW to be treated and the location influence the design of the treatment system, as do the needs and capacities of end users and operators.

## 4.0 Conclusion

This study reports the performance of a decentralized greywater treatment and reuse system which was operated for over 12 months in a government-managed school in rural India. A greywater treatment train including slow sand biofilters, anaerobic sludge bioreactors, aerators and ozonation system was installed and the performance of each of the subsystems was captured. The results show that

- The pre-treatment reduced the TSS and turbidity effectively thereby reducing the clogging and maintenance in the filtration stages.
- The filtration stages reduced the TSS, turbidity, $BOD_5$, and COD effectively.
- The high FC values at the end of the filtration stages was resolved at the ozonation stages.
- The treated GW obtained after all these stages were well within the range of the effluent discharge standards for reuse with human contact prescribed by the KSPCB.
- The overall treatment system showed RE of 99%, 98%, 66%, 73%, 98%, 96% and >99.99% in turbidity, TSS, $NO_3^-$, TP, $BOD_5$, COD and FC respectively.

These RE values obtained are comparable and slightly higher than the previously reported values. The decentralized approach using components that require low-maintenance and are simple to operate enabled the system to run smoothly without replacement of system components. The consistent RE for all the parameters discussed for a year of operation signifies the robustness of the system. A total of 180 kL of water was saved over the operational period of one-year which was utilized for toilet flushing.  This study establishes that a decentralized greywater treatment can be installed and operated with relative ease in a rural Indian setting. The removal efficiencies of each of the sub-systems are quantified which further enables proper selection of these sub-systems based on influent and effluent quality and demand.

## Author contribution statement

P S Ganesh Subramanian: Data curation, Formal analysis Writing- Original draft preparation and editing. Anjali V Raj: Data acquisition experiments, Writing- Reviewing and editing. Priyanka Jamwal: Writing- Reviewing and editing, Funding acquisition. Stephanie Connely: Writing- Reviewing and editing, Funding acquisition. Jagadeesh Yeluripati: Writing- Reviewing and editing, Funding acquisition. Samia Richards: Writing- Reviewing and editing, Funding acquisition. Rowan Ellis: Writing- Reviewing and editing, Funding acquisition. Lakshminarayana Rao: Design and build of the system, Writing- Reviewing and editing, Funding acquisition, Overall Supervision.

## Declaration of competing interest

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

## 5.0 Acknowledgements

The authors would like to thank the Scottish Government, The James Hutton Institute and the Indian Institute of Science for providing finances to support the research work.

The authors are thankful to the Indian Institute of Science and Ashoka Trust for Research Ecology and Environment for facilities and support.

## 6.0 Reference:

[1] Mekonnen MM, Hoekstra AY. Four billion people facing severe water scarcity. Sci Adv 2016;2:e1500323. https://doi.org/10.1126/sciadv.1500323.

[2] Parjane SB, Sane MG. Performance of grey water treatment plant by economical way for Indian rural development. International Journal of ChemTech Research 2011;3:1808–15.

[3] Kumar R, Singh RD, Sharma KD. Water resources in India 2005;89:794–811.

[4] Kant A. Composite Water Management Index (Cwmi): a National Tool for Water Measurement , Management & Improvement. 2018.

[5] Hanasaki N, Fujimori S, Yamamoto T, Yoshikawa S, Masaki Y, Hijioka Y, et al. A global water scarcity assessment under shared socio-economic pathways &ndash; Part 2: Water availability and scarcity. vol. 9. 2012. https://doi.org/10.5194/hessd-9-13933-2012.

[6] Brown CA. Greywater recycling - Risks, benefits, costs and policy. ECOplus Greywater Recycling 2005.

[7] Cosgrove WJ, Loucks DP. Water management: Current and future challenges and research directions: Water management research challenges. Water Resour Res 2015;51:4823–39. https://doi.org/10.1002/2014WR016869.

[8] Jury WA, Vaux H. The role of science in solving the world's emerging water problems. Proceedings of the National Academy of Sciences 2005;102:15715–20. https://doi.org/10.1073/pnas.0506467102.

[9] Khalid S, Shahid M, Natasha, Bibi I, Sarwar T, Shah A, et al. A Review of Environmental Contamination and Health Risk Assessment of Wastewater Use for Crop Irrigation with a Focus on Low and High-Income Countries. IJERPH 2018;15:895. https://doi.org/10.3390/ijerph15050895.

[10] Kehrein P, van Loosdrecht M, Osseweijer P, Garfí M, Dewulf J, Posada J. A critical review of resource recovery from municipal wastewater treatment plants – market supply potentials, technologies and bottlenecks. Environ Sci: Water Res Technol 2020;6:877–910. https://doi.org/10.1039/C9EW00905A.

[11] Capodaglio A. Integrated, Decentralized Wastewater Management for Resource Recovery in Rural and Peri-Urban Areas. Resources 2017;6:22. https://doi.org/10.3390/resources6020022.

[12] Lucy Allen, Christian-Smith J, Palaniappan M. Overview of Greywater Reuse: The Potential of Greywater Systems to Aid Sustainable Water Management. Pacific Institute; 2010.

[13] Eriksson E, Auffarth K, Henze M, Ledin A. Characteristics of grey wastewater. Urban Water 2002;4:85–104. https://doi.org/10.1016/S1462-0758(01)00064-4.

[14] MÜHLEMANN BIAJ. G Reywater Treatment on Household Level in Developing Countries –. Eidgennossiche Technishe Hoschule Zurich 2005:98.

[15] Gross A. Greywater reuse. Boca Raton, Florida: CRC Press; 2015.

[16] Sushmitha MB, Chanakya HN, Khuntia HK. Efficient Grey Water Treatment and Reuse Options for India—A Review. In: Ghosh SK, editor. Waste Water Recycling and Management, Singapore: Springer Singapore; 2019, p. 143–9. https://doi.org/10.1007/978-981-13-2619-6_12.

[17] Oteng-Peprah M, Acheampong MA, deVries NK. Greywater Characteristics, Treatment Systems, Reuse Strategies and User Perception—a Review. Water Air Soil Pollut 2018;229:255. https://doi.org/10.1007/s11270-018-3909-8.

[18] Boyjoo Y, Pareek VK, Ang M. A review of greywater characteristics and treatment processes. Water Science and Technology 2013;67:1403–24. https://doi.org/10.2166/wst.2013.675.

[19] Al-Jayyousi OR. Greywater reuse: towards sustainable water management. Desalination 2003;156:181–92. https://doi.org/10.1016/S0011-9164(03)00340-0.

[20] Oron G, Adel M, Agmon V, Friedler E, Halperin R, Leshem E, et al. Greywater use in Israel and worldwide: Standards and prospects. Water Research 2014;58:92–101. https://doi.org/10.1016/j.watres.2014.03.032.

[21] Abdel-Shafy HI, El-Khateeb MA, Shehata M. Greywater treatment using different designs of sand filters. Desalination and Water Treatment 2014;52:5237–42. https://doi.org/10.1080/19443994.2013.813007.

[22] Abdel-Kader AM. Studying the efficiency of grey water treatment by using rotating biological contactors system. Journal of King Saud University - Engineering Sciences 2013;25:89–95. https://doi.org/10.1016/j.jksues.2012.05.003.

[23] Antonopoulou G, Kirkou A, Stasinakis AS. Quantitative and qualitative greywater characterization in Greek households and investigation of their treatment using physicochemical methods. Science of The Total Environment 2013;454–455:426–32. https://doi.org/10.1016/j.scitotenv.2013.03.045.

[24] Couto E de A do, Calijuri ML, Assemany PP, Santiago A da F, Lopes LS. Greywater treatment in airports using anaerobic filter followed by UV disinfection: an efficient and low cost alternative. Journal of Cleaner Production 2015;106:372–9. https://doi.org/10.1016/j.jclepro.2014.07.065.

[25] Dallas S, Scheffe B, Ho G. Reedbeds for greywater treatment—case study in Santa Elena-Monteverde, Costa Rica, Central America. Ecological Engineering 2004;23:55–61. https://doi.org/10.1016/j.ecoleng.2004.07.002.

[26] Halalsheh M, Dalahmeh S, Sayed M, Suleiman W, Shareef M, Mansour M, et al. Grey water characteristics and treatment options for rural areas in Jordan. Bioresource Technology 2008;99:6635–41. https://doi.org/10.1016/j.biortech.2007.12.029.

[27] Karabelnik K, Kõiv M, Kasak K, Jenssen PD, Mander Ü. High-strength greywater treatment in compact hybrid filter systems with alternative substrates. Ecological Engineering 2012;49:84–92. https://doi.org/10.1016/j.ecoleng.2012.08.035.

[28] Katukiza AY, Ronteltap M, Niwagaba CB, Kansiime F, Lens PNL. Grey water treatment in urban slums by a filtration system: Optimisation of the filtration medium. Journal of Environmental Management 2014;146:131–41. https://doi.org/10.1016/j.jenvman.2014.07.033.

[29] Zipf MS, Pinheiro IG, Conegero MG. Simplified greywater treatment systems: Slow filters of sand and slate waste followed by granular activated carbon. Journal of Environmental Management 2016;176:119–27. https://doi.org/10.1016/j.jenvman.2016.03.035.

[30] Mandal D, Labhasetwar P, Dhone S, Dubey AS, Shinde G, Wate S. Water conservation due to greywater treatment and reuse in urban setting with specific context to developing countries. Resources, Conservation and Recycling 2011;55:356–61. https://doi.org/10.1016/j.resconrec.2010.11.001.

[31] Bolton CR, Randall DG. Development of an integrated wetland microbial fuel cell and sand filtration system for greywater treatment. Journal of Environmental Chemical Engineering 2019;7:103249. https://doi.org/10.1016/j.jece.2019.103249.

[32] Booker Nic. GREYWATER AND BLACKWATER TREATMENT STRATEGIES." Environment Design Guide, , 1-14. www.jstor.org/stable/26120249. 2001.

[33] Peter-Fröhlich A, Pawlowski L, Bonhomme A, Oldenburg M. EU demonstration project for separate discharge and treatment of urine, faeces and greywater - Part I: Results. Water Science and Technology 2007;56:239–49. https://doi.org/10.2166/wst.2007.577.

[34] Karnataka D of C operations. District census handbook. 2011.

[35] Buvaneshwari S, Riotte J, Sekhar M, Sharma AK, Helliwell R, Kumar MSM, et al. Potash fertilizer promotes incipient salinization in groundwater irrigated semi-arid agriculture. Sci Rep 2020;10:3691. https://doi.org/10.1038/s41598-020-60365-z.

[36] Ziemba C, Larivé O, Reynaert E, Morgenroth E. Chemical composition, nutrient-balancing and biological treatment of hand washing greywater. Water Research 2018;144:752–62. https://doi.org/10.1016/j.watres.2018.07.005.

[37] Uniliver Vim Bar n.d. http://www.unileverbrandsinfo.com/products/vim/bar/.

[38] APHA, Water Environment Federation, American Water Works Association. Standard Methods for the Examination of Water and Wastewater Part 9000 MICROBIOLOGICAL EXAMINATION Standard Methods for the Examination of Water and Wastewater. Standard Methods for the Examination of Water and Wastewater 1999:548.

[39] KSPCB - 2018 - KSPCB Notification Discharge Standards.pdf 2018.

[40] KSPCB - 2015 - KSPCB Notification Discharge Standards 2015.

[41] Jamwal P, Phillips D, Karlsrud K. Assessing local materials for the treatment of wastewater in open drains. Water Science and Technology 2019:895–904. https://doi.org/10.2166/wst.2019.105.

[42] Ranjan P, Prem M. Schmutzdecke- A Filtration Layer of Slow Sand Filter. International Journal of Current Microbiology and Applied Sciences 2018;7:637–45. https://doi.org/10.20546/ijcmas.2018.707.077.

[43] Shama S, Iffat N. Role of the Biofilms in Wastewater Treatment. vol. i. 2016. http://dx.doi.org/10.5772/63499.

[44] Unger MC. The role of the schmutzdecke in Escherichia coli removal in slow sand and riverbank filtration. n.d.

[45] Wang X, Ji M, Wang JF, Liu Z, Yang ZY. Anaerobic uptake of phosphate in an anaerobic–aerobic granular sludge sequencing batch reactor. Water Science and Technology 2006;53:63–70. https://doi.org/10.2166/wst.2006.266.

[46] Keating C, Chin JP, Hughes D, Manesiotis P, Cysneiros D, Mahony T, et al. Biological Phosphorus Removal During High-Rate, Low-Temperature, Anaerobic Digestion of Wastewater. Front Microbiol 2016;7. https://doi.org/10.3389/fmicb.2016.00226.

[47] Hernández-Leal L, Temmink H, Zeeman G, Buisman CJN. Removal of micropollutants from aerobically treated grey water via ozone and activated carbon. Water Research 2011;45:2887–96. https://doi.org/10.1016/j.watres.2011.03.009.

[48] Dong S, Li J, Kim M-H, Park S-J, Eden JG, Guest JS, et al. Human health trade-offs in the disinfection of wastewater for landscape irrigation: microplasma ozonation vs. chlorination. Environ Sci: Water Res Technol 2017;3:106–18. https://doi.org/10.1039/C6EW00235H.

[49] Wastewater Technology Fact Sheet-Ozone Disinfection 1999.

[50] Rao H, Rao L, Haridas H, Manju DK, Swetha S, Chanakya H. Design and Characterization of Cold Plasma Ozonator for Wastewater Treatment. In: Ghosh SK, Saha PD, Francesco Di M, editors. Recent Trends in Waste Water Treatment and Water Resource Management, Singapore: Springer Singapore; 2020, p. 159–69. https://doi.org/10.1007/978-981-15-0706-9_16.

[51] Moghadam AK, Dore M. Cost and Efficacy of Water Disinfection Practices: Evidence from Canada 2012:15.

[52] Safewater-Chlorination. Centers for Disease Control and Prevention 2014. https://www.cdc.gov/safewater/chlorination.html (accessed September 13, 2020).

[53] Wastewater Technology Fact Sheet-Ultraviolet Disinfection 1999.

[54] Rosa Raudales, Paul Fisher, Charlie Hall. How Much Does It Cost to Sanitize Your Water? Greenhouse Product News 2017. https://gpnmag.com/article/how-much-does-it-cost-to-sanitize-your-water/ (accessed September 13, 2020).

[55] Ladu JLC. Effects of hydraulic retention time, temperature, and effluent recycling on efficiency of anaerobic filter in treating rural domestic wastewater n.d.:15.