Greywater treatment for reuse: comparison of reuse options using analytic hierarchy process

Dilip M. Ghaitidak and Kunwar D. Yadav

ABSTRACT

The objective of the present study was to: (i) examine the performance of two-stage sand filtration and the effect of coagulants on greywater (GW) characteristics; (ii) assess the quality of treated GW for reuse; and (iii) compare reuse options using the analytic hierarchy process (AHP). Four treatment options were examined on site. The first option was related to two-stage sand filtration (TSF) and the other three options were related to coagulation/flocculation using alum, polyaluminium chloride (PAC), and ferric chloride ($FeCl_3$). The setup was constructed close to the GW source of a student hostel located at Sardar Vallabhbhai National Institute of Technology (SVNIT), Surat. Treated GW was safe for reuse in restricted access area irrigation (as per United States Environmental Protection Agency standards), for discharge into land for irrigation, and for industrial cooling (as per Central Pollution Control Board standards in India). All four treatment options were compared using AHP. Comparison was made in two ways: (1) comparison on the basis of the effluent quality produced and (2) comparison on the basis of removal of parameters. The selection string on the basis of the effluent quality was TSF-PAC treatment–alum treatment–$FeCl_3$ treatment, and that on the basis of removal of parameters was TSF-PAC treatment–$FeCl_3$ treatment–alum treatment.

Key words | analytic hierarchy process, coagulation, greywater reuse, on-site treatment, ranking, sand filtration

Dilip M. Ghaitidak (corresponding author)
Kunwar D. Yadav
Department of Civil Engineering,
SV National Institute of Technology (SVNIT),
Surat 395007,
India
E-mail: *dmghaitidak@gmail.com*

INTRODUCTION

Greywater (GW) is wastewater from the kitchen, bath, and laundry, excluding wastewater from toilets (WHO 2006; Gross *et al.* 2007). Light greywater (LGW) is the GW from bathroom, showers, tubs, and clothes washing machine sources. In a household, the proportion of GW flow is around 50 to 80% of the total wastewater flow (Christova-Boal *et al.* 1996). LGW is around 47% of GW (Ghaitidak & Yadav 2013). Hence, GW reuse can be an effective measure for saving water on the domestic level and reducing the load on wastewater treatment plants.

At present, a limited number of studies have been reported on LGW using sand filters. Ghaitidak & Yadav (2015) examined the effect of coagulants under variable pH conditions. In the present scenario, the technologies are developed just to check the efficiency of a particular system. There is a need to develop technologies by targeting the type of reuse (e.g., agriculture, gardening, flushing, washing, etc.). It is observed that a single method/technology is not capable of meeting the entire reuse standards, so there is a need to develop a flow diagram with a combination of different technologies by targeting the type of reuse. A summary of reported research on on-site GW treatment by filtration and use of coagulants is given in Table 1.

When options are compared on the basis of a single criterion, they can be compared simply by arranging them in descending or ascending order. In the case of beneficial (e.g., profit, % removal, etc.) criteria, the options are arranged in descending order of criterion value and for non-beneficial criteria (e.g., cost, effluent concentration,

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Table 1 | Summary of reported research on on-site greywater treatment by filtration and use of coagulants

Reference	Main features	Main conclusions	Remarks
Filtration			
Finley *et al.* (2009)	Tested bath, shower, washing machine GW	No significant difference in contamination levels was observed between crops irrigated with tap water, untreated GW, and treated GW	Results reinforce the potential of domestic GW as an alternative irrigation source
	Treatment using PST (HRT 8 h) followed by coarse filtration (HRT 24 h)		Study was not referred to any reuse standards
	Tested impact of irrigating vegetable crops		Adopted very high HRT
Mandal *et al.* (2011)	Tested bath, wash basin GW	Concluded that GW generated from a household is self-sufficient to irrigate a small garden.	Study conducted for 2 months (May and June)
	Treatment using filtration followed by aeration and disinfection		Tested only two samples
Katukiza *et al.* (2014)	Tested bath, kitchen, and laundry GW	*Escherichia coli* log removal was >3 but could not satisfy WHO standards	Tested in batch mode
	Treatment using PST followed by filtration		Quantity treated was limited to 40 L/d
Coagulants			
Friedler & Alfiya (2010)	Tested bath, washbasin GW	Most of the removal occurred in the coagulation-sedimentation step, while the filter acted as a polishing unit	Involves large electricity consumption
	Treatment using ferric chloride coagulation, sedimentation and filtration		Operated in semi-batch mode
	Doses reported in terms of Fe		
Kariuki *et al.* (2011)	Tested kitchen, laundry, hand basin greywater	GW treatment system could produce effluent complying with pathogen limit in the referred standards	Alum dose was not optimized
	Pilot-scale study		Economic evaluation was not reported
	Treatment using alum coagulation followed by disinfection		Important reuse parameters like BOD_5, TSS were not monitored

BOD_5, 5-day biochemical oxygen demand; TSS, total suspended solids; PST, plain settling; HRT, hydraulic retention time.

etc.), options are arranged in ascending order. The option placed at the top will be the optimal option and the option placed at the bottom will be the least preferred option. However, comparison of options mostly involves multiple criteria, and selection of the optimal option becomes a complex situation. Therefore, comparison of options with multiple criteria needs a mathematical technique for scientific comparison. In the present study, treatment options were compared using the analytic hierarchy process (AHP).

AHP is a well-known multi-criteria decision-making method that has been widely applied to solve problems in many fields (Vaidya & Kumar 2006; Ishizaka & Labib 2011). However, applications of multi-criteria decision-making to GW investigations are quite limited. Chen *et al.* (2012) applied the preference ranking organization method for enrichment evaluation (PROMETHEE) for selecting a recycling alternative in a household laundry in Sydney. The present study gives a step-by-step solution for the use of AHP in selecting the optimal option in LGW investigations. In view of the above, the objective of the present study was to: (i) examine the performance of two-stage sand filtration and the effect of coagulants on GW characteristics; (ii) assess the quality of treated GW for reuse; and (iii) compare reuse options using AHP.

MATERIALS AND METHODS

Greywater, filter media, and coagulants

Greywater was collected from a student hostel (capacity 474 students) located at Sardar Vallabhbhai National Institute of Technology (SVNIT), Surat, India. The GW collection pipe was cut and GW was diverted to a collecting tank of 500-L capacity.

Naturally available river sand was used for preparation of the filters. Coarse sand (2 mm–4.75 mm), medium sand (1 mm–2 mm), and fine sand (0.125 mm–1 mm) were used. Sand was washed with potable water and sun dried. The sand was stocked in separate piles according to size, viz. coarse, medium, and fine.

Alum ($Al_2(SO_4)_3.18H_2O$), polyaluminium chloride (PAC), and ferric chloride ($FeCl_3$) coagulants were used in the study. The alum contained 4.75% Al, the PAC contained 15.07% Al, and the $FeCl_3$ contained 30.97% Fe on a weight basis. The stock was prepared regularly by dissolving 12–36 g coagulant in 1,000 mL distilled water. Normally, the entire stock was required in each coagulation run. Analytical grade coagulants were used in the entire study.

Analytical procedures

The raw and treated GW samples were analyzed using *Standard Methods* (APHA 2005). Analytical grade chemicals were used in the study. Parameter pH was measured using a digital pH meter (Hanna Instruments pH 209); turbidity was measured using a digital Nephelo turbidity meter (Systronics Turbidity Meter 132); and electrical conductivity (EC_{25}) was measured using a digital conductivity meter (Systronics Conductivity TDS Meter 308). Standardization of the instruments was checked each day before sample analysis to ascertain their proper working condition. Solids were measured by drying the samples in a hot air oven at $105 \pm 2/180 \pm 2\ ^\circ C$. Oil and grease (O&G) were analyzed by the partition-gravimetric method using petroleum ether ($40\ ^\circ C/60\ ^\circ C$). Phosphate ($PO_4$-P) was analyzed by the stannous chloride method. Dissolved oxygen in the biochemical oxygen demand test was analyzed as per the Winkler method with azide modification. Chemical oxygen demand (COD) was analyzed by the open reflux method using potassium dichromate ($K_2Cr_2O_7$) as an oxidizing agent. Metals and earth elements (Ca, Mg, Na, B, As, Al, Fe) were analyzed using an inductively coupled plasma-atomic emission spectrometer (ARCOS, M/s, Spectro, Germany).

Total coliforms (TC) and fecal coliforms (FC) were analyzed by the multiple-tube fermentation technique (five tubes, three dilutions). A presumptive test for coliforms was performed using McConkey broth (HiMedia Laboratories Pvt. Ltd, Mumbai, India) by incubating at $35 \pm 0.5\ ^\circ C$ for 24 h. Further, TC were confirmed using Brilliant Green Bile Broth (HiMedia) by incubating at $35 \pm 0.5\ ^\circ C$ for 24 h; and FC were confirmed using EC broth (HiMedia) by incubating at $44.5 \pm 0.2\ ^\circ C$ for 24 h. Results were expressed as most probable number (MPN)/100 mL. *Escherichia coli* were measured by the pour plate method using EMB agar (HiMedia) by incubating at $37\ ^\circ C$ for 24 h, and results were expressed as colony forming units (CFU) per 100 mL.

Greywater treatment options

The setup was constructed on-site close to the GW source of a student hostel located at SVNIT, Surat. Fresh GW was collected continuously in a greywater collection tank (GWCT) of 500-L capacity after primary screening to remove the floating matter and further passed through a coarse sand filter. The study was divided in two parts. Part I deals with two-stage sand filtration and Part II deals with the effect of coagulants. The collected GW was first filtered through a coarse sand filter. Then it was passed through either two-stage sand filters or a coagulation/flocculation (COF) unit. The entire flow in the system was under gravity. A conceptual flow diagram of the experimental setup is shown in Figure 1.

Part I: performance of two-stage sand filtration in greywater treatment

This part pertains to option 1. This option refers to the two-stage sand filtration (TSF) in this study. Two identical sand filters were operated in series in continuous mode. In the first stage, the effluent of the coarse sand filter was passed through sand filter stage I (SF1). In stage two, the effluent of the SF1 was passed through sand filter stage II (SF2). Filters were operated in the submerged mode. Filters were

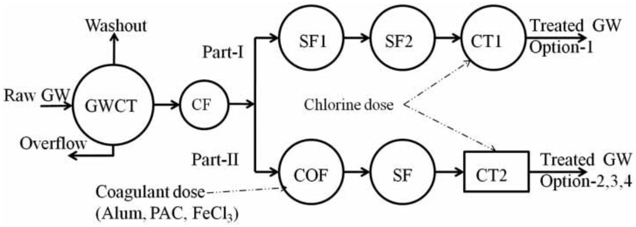

Figure 1 | Conceptual flow diagram of experimental setup. GWCT, raw greywater collection tank; CF, coarse sand filter; SF1, sand filter stage I; SF2, sand filter stage II; COF, coagulation/flocculation; SF, sand filter; CT1, treated water collection tank 1; CT2, treated water collection tank 2; Option-1: raw GW-CF-SF1-SF2-disinfection; Option-2: raw GW-CF-alum coagulation-SF-disinfection; Option-3: raw GW-CF-PAC coagulation-SF-disinfection; Option-4: raw GW-CF-$FeCl_3$ coagulation-SF-disinfection.

exposed to the atmosphere and covered by nylon mosquito net to avoid mosquitoes and flies breeding. GW treated using two-stage sand filtration was further disinfected using bleaching powder.

Coarse sand filter

A polyvinyl chloride (PVC) cylindrical container was used for fabricating the coarse sand filter (CF) used in the study. The CF had an internal diameter of 33 cm and depth of 56 cm. Figure 2 shows the schematic diagram of the mini coarse sand filter and coarse sand filter used in this study. The CF contained a removable mini coarse sand filter (MCF) inside. A small 3-L capacity plastic bucket half filled with sand (the same sand as in the CF) was used as the MCF. The raw GW flowing from the GWCT was first passed through the MCF and then passed through the CF. The MCF was cleaned daily using potable tap water. The hydraulic retention time (HRT) of the GW in the CF was 1 h at 10 L/h flow rate.

Sand filter stage I/II (SF1/SF2)

GW filtered from the CF was further treated using the two-stage sand filtration unit. A PVC container of 104 L capacity was used for fabricating the sand filter. The filter medium comprises coarse sand, medium sand, and fine sand. The effective size (D_{10}) and uniformity coefficient (Cu) of the fine sand used were 0.25 mm and 2.8, respectively. The initial pore volumes in SF1 and SF2 were 26% each. A schematic diagram of the sand filters (SF1/SF2) is shown in Figure 3. Filters SF1 and SF2 were operated in series. The flow was in a downward direction and the filters were operated in submerged mode.

Part II: effect of coagulants on greywater characteristics

This part pertains to option 2, option 3, and option 4, and refers to alum treatment, PAC treatment, and $FeCl_3$ treatment, respectively, in the present study.

Coagulation/flocculation unit

The COF unit comprises a 1 L capacity plastic jar (PJ), an aquarium aerator, coagulant feeder tank (CO), and a

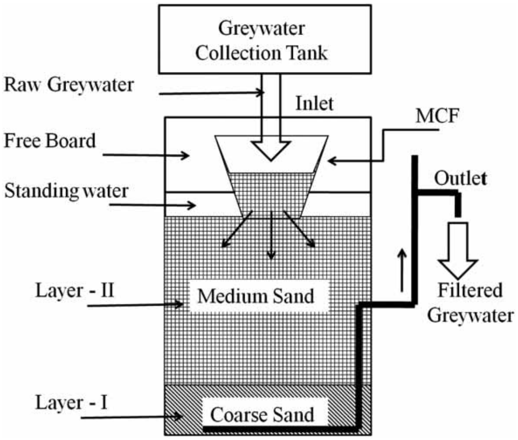

Figure 2 | Schematic diagram of mini coarse sand filter and coarse sand filter. Layer-I, size 2,000–4,750 mm and depth 5 cm; Layer-II, size 1,000–2,000 mm and depth 32 cm.

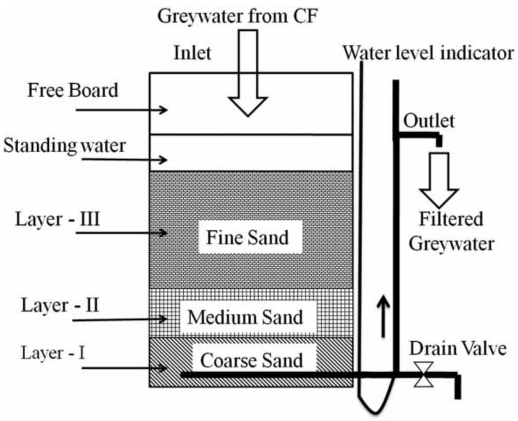

Figure 3 | Schematic diagram of sand filter SF1/ SF2. CF, coarse sand filter; Layer-I, size 2,000–4.750 mm and depth 5 cm; Layer-II, size 1,000–2,000 mm and depth 5 cm; Layer-III, size 0.125–1,000 mm and depth 46 cm.

flocculation-cum-settling tank (FST). Figure 4 shows a schematic diagram of the coagulation/flocculation unit. A plastic jar was kept in suspension in a just submerged condition in the FST. An aquarium aerator of 3 L/min capacity (consumption 3 W, 220–240 V) was used for rapid mixing of the coagulant. One outlet of the aerator was connected to the CO, and another outlet was connected to the PJ. A supply of air was required in the CO to keep the coagulant uniformly mixing and ensure a uniform coagulant concentration.

The coagulant and coarse filtered GW was first diverted into the PJ, which acts as a coagulation-cum-rapid mixing tank. Air injected by the aerator creates rapid turbulence. The turbulence thus created causes breaking down of the zeta potential, mixing of the coagulant with the GW, and gives upward/lateral movement to the GW leaving the PJ. A PVC container of 47 L capacity (diameter 33 cm, depth 56 cm) was used as the FST. The FST provides the space for floc formation, floc aggregation, and settling. The HRT of the FST was 2 h at 20 L/h flow rate. The effluent from the FST was further filtered using a sand filter.

In the present study, rapid mixing was adopted by using a pneumatic method (i.e., diffused air). The temporal mean velocity gradient (G) was calculated using Equation (1):

$$G = \left(\frac{P}{\mu * \mathrm{vol}}\right)^{0.5} \tag{1}$$

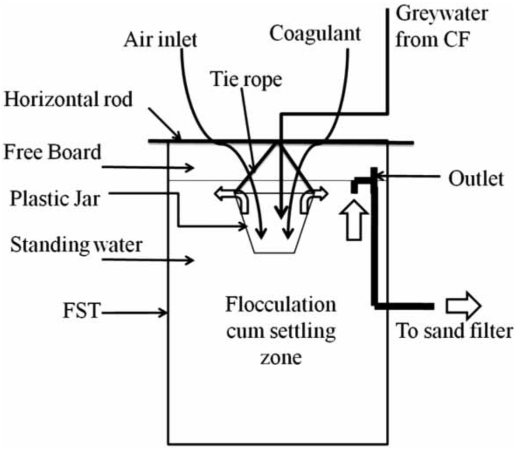

Figure 4 | Schematic diagram of the coagulation/ flocculation unit. CF, coarse sand filter; FST, flocculation-cum-settling tank.

where P = total input of power in watts; μ = absolute viscosity of greywater, in N.S/m^2; vol = volume of the rapid mix unit, in m^3.

Sand filter (non-submerged)

Water passing through the coagulation/flocculation unit was further treated using a sand filter (SF). The filter configuration was the same as that of the SF1/SF2. However, this filter was operated in non-submerged mode. Filtrate from the SF was collected through a drain valve so as to operate it in non-submerged mode.

Disinfection of treated greywater

Greywater treated in both parts was disinfected using bleaching powder (BP). The available chlorine in the BP was 22% by weight. The chlorine dose was added to the treated GW and residual chlorine was measured after 30 min contact time.

Statistical analysis

Statistical analysis of the results was performed using Excel 2007 and SYSTAT (Sigmaplot 12). A paired t-test (paired two sample for means) was performed on parameters monitored before and after the treatment. This test was appropriate in the present study because: (1) parameters before and after the treatment were compared, and they were of the same size; and (2) the parameters compared were a continuous variable.

The null (H_0) and alternate hypothesis (H_1) framed in the t-test were (Equations (2) and (3)):

$$H_0: \mu_R = \mu_T \tag{2}$$

$$H_1: \mu_R \neq \mu_T \tag{3}$$

where μ_R and μ_T were mean concentrations of the parameters in raw and treated GW, respectively. μ_T can be replaced subsequently as μ_1, μ_2, μ_3, and μ_4, which correspond to option 1, option 2, option 3, and option 4, respectively.

The level of test significance was 95%. A p-value < 0.05 indicates that H_0 can be rejected, which means the mean concentration of the parameters differs significantly after treatment. A *p*-value >0.05 indicates failure to reject H_0, which means the mean concentration of the parameters does not differ significantly after treatment.

Analytic hierarchy process

The AHP is a method based on priority theory, and is capable of: (i) breaking down a complex problem into its component parts; (ii) arranging these components in a hierarchy model; and (iii) assigning numerical values to criteria based on their subjective judgments (Saaty 1980; Rao 2007).

In the present study, the geometric mean method of AHP was used. This method of AHP is commonly used to determine the priority weights of the attributes owing to its simplicity, easy means of finding the maximum Eigen value, and reduction in inconsistency of judgments.

To decide the importance of the attributes, an expert opinion survey was conducted. Table 2 presents the comparison scale used in AHP and corresponding linguistic variables used in the survey in the present study. A questionnaire containing the list of the criteria/attributes was circulated among environmental experts and their responses regarding the importance to be assigned to the attributes were collected in the linguistic form on the basis of the comparison scale proposed by Saaty (1990). The linguistic variables were converted to the absolute numbers. The average values of the responses of the experts were considered in forming the relative importance matrix.

RESULTS AND DISCUSSION

Performance of coarse filtration in greywater treatment

Filtration was carried out in continuous mode. Every week the GWCT was completely emptied by operating outlet valves kept at the bottom for draining purposes. This was necessary to avoid the accumulation of solids and contaminants in the GWCT. Characteristics of the raw and coarse filtered GW are given in Table 3.

Part I: performance of two-stage sand filtration in greywater treatment

The flow rate was adjusted to 10.2 ± 0.46 L/h. Greywater treated using two-stage sand filtration was further disinfected using bleaching powder. The average hydraulic loading rate, organic loading rate, and HRT observed in the filtration study were as given in Table 4.

Table 2 | The comparison scale used in AHP and linguistic variables assigned

Intensity of importance	Definition	Explanation	Linguistic variable
1	Equal importance	Two activities contribute equally to one objective	Extremely low
2	Intensity of importance (II) between 1 and 3	–	Very low
3	Moderate importance of one over another	Judgment slightly favors one activity over another	Low
4	II between 3 and 5	–	Below average
5	Strong importance	Judgment strongly favors one activity over another	Average
6	II between 5 and 7	–	Above average
7	Very strong importance	An activity is strongly favored and its dominance is demonstrated in practice	High
8	II between 7 and 9	–	Very high
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation	Extremely high

Note: reciprocals of the above non zero – if activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*.

Table 3 | Characteristics of raw and coarse filtered greywater

		Raw greywater		**CF effluent**	
Parameter	**n**	**Min–max**	**Avg ± SD**	**Min–max**	**Avg ± SD**
pH	85	6.62–8.13	7.49 ± 0.30	6.4–8.34	7.52 ± 0.29
Turbidity, NTU	85	5.7–190.0	80.3 ± 30.5	3.1–98.1	39.2 ± 16.2
Temperature, °C	85	22.2–30.4	28 ± 2.9	21.6–30.7	26 ± 2.9
EC_{25}, μS/cm	85	269–646	489 ± 83	265–637	482 ± 84
Total dissolved solids (TDS), mg/L	77	184–396	304 ± 53	182–406	299 ± 53
TSS, mg/L	77	24–215	88 ± 30	14–176	70 ± 24
Oil and grease (O&G), mg/L	59	4–80	33 ± 13	3–58	23 ± 9
Alkalinity, mg/L	79	152–260	187 ± 15	144–248	171 ± 16
BOD_5, mg/L	63	30–306	102 ± 49	15–290	87 ± 43
COD, mg/L	58	68–596	243 ± 101	44–556	224 ± 95
Total coliforms (TC), MPN/100 mL	15	3.10×10^5–4.90×10^7	$1.88 \times 10^7 \pm 9.86 \times 10^6$	2.10×10^5–2.10×10^7	$7.90 \times 10^6 \pm 7.00 \times 10^6$
Fecal coliforms (FC), MPN/100 mL	15	1.20×10^4–8.40×10^5	$2.83 \times 10^5 \pm 3.46 \times E^5$	9.30×10^3–7.20×10^5	$1.90 \times 10^5 \pm 3.20 \times 10^5$
E. coli, CFU/100 mL	15	3.00×10^2–2.10×10^3	$9.71 \times 10^2 \pm 5.24 \times 10^2$	4.00×10^2–1.70×10^2	$9.10 \times 10^2 \pm 4.60 \times 10^2$
Sodium adsorption ratio (SAR)	8	1.40–3.60	2.30 ± 0.37	–	–
Boron, mg/L	8	0.05–0.10	0.07 ± 0.01	–	–
Arsenic, mg/L	8	< 0.01	< 0.01	–	–
Ammonia nitrogen (NH_3-N), mg/L	61	0.50–3.90	2.00 ± 0.93	0.30–3.36	1.69 ± 0.81
Phosphates (PO_4-P), mg/L	42	0.20–1.90	0.95 ± 0.24	0.10–1.80	0.87 ± 0.23

n, number of samples; Avg, arithmetic average; SD, standard deviation; CF, coarse sand filter.

Table 4 | Average loading rates during two-stage filtration study

		Organic loading rate		
Filter	**Hydraulic loading rate ($L.h^{-1}.m^{-2}$)**	**(kg BOD_5. $m^{-2}.d^{-1}$)**	**(kg BOD_5. $m^{-3}.d^{-1}$)**	**HRT (h)**
Sand filter stage I (SF1)	70.2	0.153	0.309	2.4
Sand filter stage II (SF2)	70.2	0.089	0.180	2.4

Four filtration runs were conducted for durations of 38, 53, 36, and 31 days in runs 1, 2, 3, and 4, respectively. At the end of each run the entire filter medium was removed and washed using potable water. The medium was dried and refilled in each filter before commencing the next run. Filter head loss at filter SF1 was monitored in run 3 and run 4. In run 3, the head loss was greatest (120 mm) on day 36, and in run 4 the head loss was greatest on day 31, when the filter started overflowing. The head loss observed in both the runs is shown in Figure 5. In run 3, the head loss in the filter was governed by Equation (4) with an R^2 value of 0.989. In run 4, the head loss was governed by Equation (5) with an $R^2 = 0.987$.

$$y = 0.084x^2 - 0.092x + 14.78 \tag{4}$$

$$y = 0.118x^2 - 8.929x + 180.2 \tag{5}$$

where y = head loss (mm); x = run days.

The initial pore volume of the filter (SF1, SF2) was around 26%, which gradually reduced to 14% at the end of the run. The effective HRT varied from 2.4 to 1.7 h at a flow rate of 10 L/h. Thus, the combined HRT of both the filters varied from 4.8 to 3.4 h.

Characteristics of filtered greywater

The effect of filtration on GW characteristics is presented in Table 5 (see option 1). The mean raw GW pH was changed

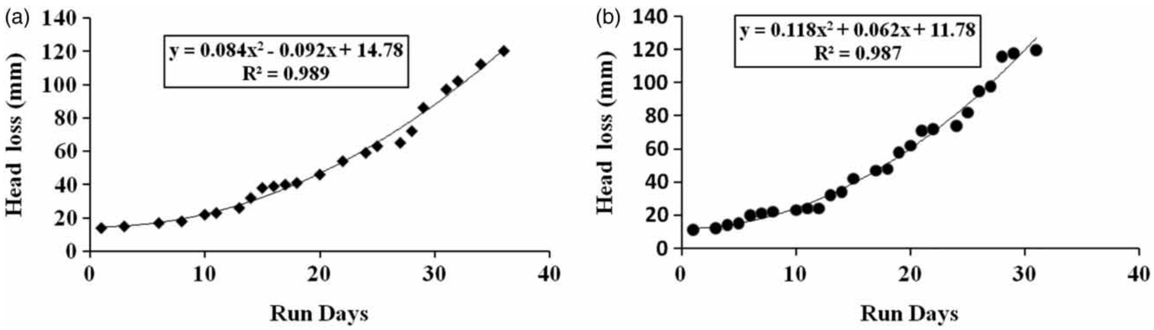

Figure 5 | Head loss in sand filter: (a) run 3, (b) run 4.

Table 5 | Mean raw and treated GW characteristics observed in each treatment option

	Option 1 (TSF)		Option 2 (Alum treatment)		Option 3 (PAC treatment)		Option 4 ($FeCl_3$ treatment)	
Parameter	**Raw**	**Treated**[a]	**Raw**	**Treated**[b]	**Raw**	**Treated**[c]	**Raw**	**Treated**[d]
pH	7.51	7.24	7.51	7.44	7.66	7.37	7.57	7.54
Turbidity, NTU	83.4	4.5	89.6	0.9	83.8	0.6	77.7	2.3
Electrical conductivity, μS/cm	488	465	454	495	497	520	500	523
Total suspended solids, mg/L	92	15	83	5	94	4	92	7
Oil and grease, mg/L	35	8	30	1	31	2	31	3
BOD_5, mg/L	106	28	95	11	113	7	105	15
Boron, mg/L	0.071	0.010	0.063	0.010	0.079	0.010	0.07	0.010
Sodium adsorption ratio	2.36	2.00	1.55	1.50	3.10	2.35	2.45	2.15
Fecal coliforms, MPN/100 mL	1.97×10^5	< 2	2.50×10^5	< 2	1.40×10^5	< 2	2.60×10^5	< 2

[a] Final effluent from option-1.
[b] final effluent from option-2.
[c] final effluent from option-3.
[d] final effluent from option-4; TSF, two-stage sand filtration.

from 7.51 to 7.38, 7.19, and 7.24 in CF, SF1 and SF2 effluent, respectively. Similarly, mean alkalinity was also changed from 187 mg/L to 171, 154, 140 mg/L in CF, SF1 and SF2 effluent, respectively. Soap was a major contributor to the alkalinity. As the suspended solids (soap particles) were trapped in the reactor CF, SF1 and SF2 progressively, alkalinity was reduced. A drop in pH and alkalinity in SF1 and SF2 effluents may also be due to the release of H^+ ions during the nitrification process.

The effect of filtration on turbidity and total suspended solids (TSS) is shown in Figures 6 and 7, respectively. Mean raw GW turbidity was reduced from 83.4 NTU to 40.3, 7.9, 4.5 NTU and mean raw GW TSS was reduced from 92 mg/L to 73, 34, 15 mg/L, in CF, SF1 and SF2 effluent, respectively. Turbidity is an indirect measure of the TSS and colloidal solids. Hence, the reduction in TSS and colloidal solids leads to the reduction of turbidity. In a similar study, using a four barrel gravel filter, Al-Hamaiedeh & Bino (2010) observed a

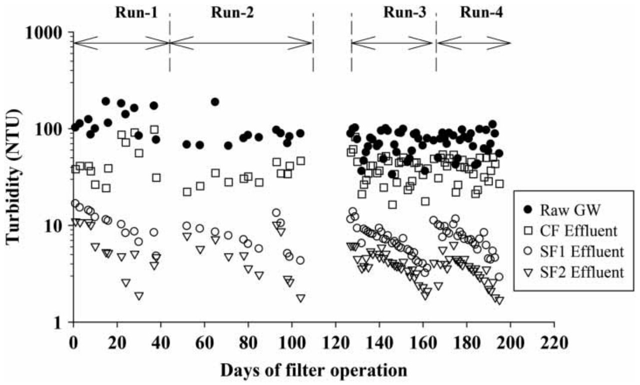

Figure 6 | Performance of sand filtration on turbidity. CF, coarse sand filter; SF1, sand filter stage I; SF2, sand filter stage II.

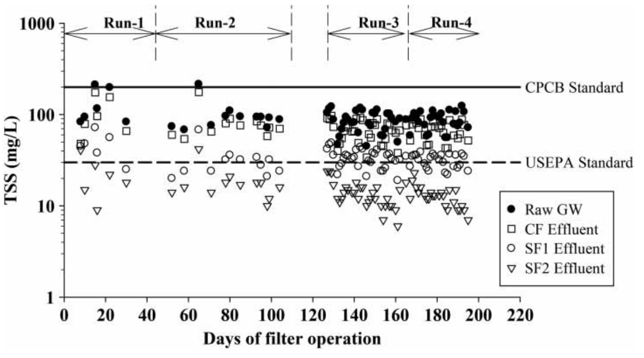

Figure 7 | Performance of sand filtration on total suspended solids. CPCB (1993; 2008) standard: 200 mg/L max; USEPA (2004) standard: 30 mg/L max; CF, coarse sand filter; SF1, sand filter stage I; SF2, sand filter stage II.

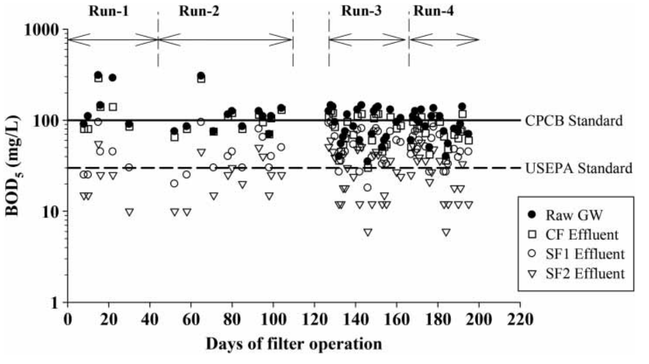

Figure 8 | Performance of sand filtration on biochemical oxygen demand. CPCB (1993, 2008) standard: 100 mg/L max; USEPA (2004) standard: 30 mg/L max; CF, coarse sand filter; SF1, sand filter stage I; SF2, sand filter stage II.

reduction in TSS from 275 mg/L to 150 mg/L (removal 46%). Mandal *et al.* (2011) observed turbidity removal of 38.7 to 9.6 NTU (removal of 75%), and TSS removal of 17.6 to 12 mg/L (removal of 32%). Karabelnik *et al.* (2012) observed 86–90% TSS removal using a vertical filter (4–10 mm size crushed Filtralite® media) at a flow rate of 80 L/d.

In the present study, mean turbidity removal was 51.7, 90.5, and 94.6% and mean TSS removal was 20.7, 63.0, and 83.7% in CF, SF1 and SF2 effluent respectively. The better turbidity and TSS removal obtained in the present study may be due to use of fine sand filter media. The % removal of turbidity and TSS was below average in the first 8–10 days of the filter run. In the last 3–4 days of the filter run, removal was above average. Initially, at the time of commissioning, the filter pores of the media were empty; however, as the volume of GW filtered went on increasing, the filter pores gradually reduced, thereby enabling the filter media to trap the finer particles. Thus, the rate of removal increased as the filter proceeded towards maturity. The dominant mechanisms responsible for removal of turbidity and TSS may be straining and sedimentation within the granular medium.

The mean O&G concentration was reduced from 35 to 24, 11, and 8 mg/L in CF, SF1 and SF2 effluent, respectively. The corresponding removal was 31.4, 68.6, 77.1%, respectively. Since all the three reactors were operated in submerged mode, a few cm depth of standing water was always above the sand bed. The specific gravity of O&G is less than that of GW. Hence, the O&G was trapped in the standing water in the reactor.

The effect of filtration on 5-day biochemical oxygen demand (BOD_5) is shown in Figure 8. The mean BOD_5 concentration was reduced from 106 mg/L to 91, 53, and 28 mg/L in CF, SF1 and SF2 effluent, respectively. The corresponding mean removal was 14.2, 50.0, and 73.6% respectively. In the first 8–10 days, the removal rate was below average, whereas the removal was above average in the next days of the run. As the filter progressed, the filter pores became clogged due to trapping of solids. The biological slime layer developed after 8–10 days and became attached on the top layer of the media in the SF1 and SF2 reactors. The slime layer contains mainly facultative bacteria, fungi, algae, and protozoans (Metcalf & Eddy Inc. 2003). Removal of BOD was through the combined action of physical and biological processes. Prior to development of the slime layer, physical processes such as straining, sedimentation, and adsorption may be dominant, which mainly removed suspended BOD. However, after development of the slime layer, both physical and biological mechanisms played a significant role. Microorganisms in the slime layer degrade organic matter (dissolved) as the GW passes down through it. Over a period of time, as the thickness of the slime layer increases, the slime layers may act as a fine straining mat and improve the removal of fine particles contributing to BOD. Hence, in the last few days of the run, the BOD removal was above average due to the combined physical and biological removal mechanisms.

In a similar study, Al-Hamaiedeh & Bino (2010) obtained a BOD_5 removal from 942 mg/L to 108 mg/L (removal of 88%). In the present study mean BOD_5 removal was around 70% with a residual BOD_5 of 29 mg/L. The percentage removal was slightly lower, but the final effluent quality was better than that reported by Al-Hamaiedeh & Bino (2010). The better quality of the effluent obtained in the present study may be due to the use of a fine sand medium and the contribution of bacterial slime developing on the top medium layer in the filter.

The mean TC count of 9.10×10^6 MPN/100 mL was reduced to 8.27×10^6, 2.77×10^5, 2.29×10^4 MPN/100 mL; the FC count was reduced from 2.38×10^5 to 1.97×10^5, 2.11×10^4, 2.17×10^3 MPN/100 mL; and the *E. coli* count was reduced from 9.35×10^2 CFU/100 mL to 9.20×10^2, 7.00×10^2, 4.80×10^2 CFU/100 mL, in CF, SF1 and SF2 effluent, respectively. The mean log10 removal of TC was 0.04, 1.52, and 2.6; removal of FC was 0.08, 1.05, and 2.04; and *E. coli* removal was 0.01, 0.13, and 0.29 in CF, SF1 and SF2 effluent, respectively. The microorganisms in the bio-layer consumed the pathogens in the GW (CAWST 2008). A better removal of pathogens was observed in the present study. This may be due to the removal by microorganisms in the bio-layer, and die-off in the lower layer of the filter due to lack of food and oxygen. The dissolved oxygen level in filtration effluents (SF1 and SF2) were of the order of 0.2 to 0.4 mg/L.

Katukiza *et al.* (2014) obtained *E. coli* removal of 1.595 (log10). This is higher than that in the present study. Katukiza *et al.* (2014) operated filters in batch mode treating only 40 L/d of GW, whereas the present study was a continuous mode operation treating 240–250 L/d. The lesser removal of *E. coli* observed in the present study may be due to the continuous mode operation and treating a greater quantity of GW compared to that in the cited research.

Part II: effect of coagulants on greywater characteristics

Greywater was filtered using a coarse sand filter and coagulated using alum, PAC, and $FeCl_3$. Coagulated GW was filtered using a sand filter and was disinfected using bleaching powder. Floc size in the alum and PAC coagulation was up to 3 mm, and in $FeCl_3$ was up to 2 mm. Owing to a continuous flow of GW, the flocs were escaping from the coagulation tank; therefore, the filtration was essential to trap the flocs/solids from the coagulated water. A sand filter (SF) was provided for entrapment of the flocs from the coagulated GW.

Rapid mixing and settling

A total of 36 coagulation runs (average 12 runs/coagulant) were conducted in the present study. From the laboratory-scale study the optimum coagulant dose was observed as 351 ± 78, 190 ± 37, and 107 ± 28 mg/L using alum, PAC, and $FeCl_3$, respectively (Ghaitidak & Yadav 2014). They were roughly in the ratio of Alum:PAC:$FeCl_3$ = 3:2:1. Therefore, the coagulant doses used in the on-site study were maintained in the same proportion. The doses applied were 416 ± 44, 279 ± 40, and 141 ± 12 mg/L, in alum, PAC, and $FeCl_3$, respectively. The coagulant doses used in the present study were kept slightly higher than that in the laboratory-scale study due to unfavorable coagulation/flocculation facilities available on-site.

As per CPHEEO (1999), design criteria for rapid mix unit are: detention time = 30 to 60 s; temporal mean velocity gradient $(G) > 300\ s^{-1}$ (range 300 to $5{,}000\ s^{-1}$); power requirement = 1 to 3 W per m^3/h flow. In the present study power used was 1.5 W, volume of the mixing container was 1 L. Assuming $\mu = 0.798 \times 10^{-3}$ (@ 30 °C temperature), G is $1{,}371\ s^{-1}$. The detention time at 20 L/h flow rate is 180 s.

Characteristics of treated greywater

The effect of coagulants on GW characteristics is given in Table 5 (see option-2, -3, -4 for alum, PAC, and $FeCl_3$, respectively). Mean alkalinity was reduced from 186 mg/L to 177, 63, and 59 mg/L in alum treatment; it was reduced from 189 mg/L to 174, 78, and 83 mg/L in PAC treatment; and reduced from 190 mg/L to 177, 85, and 82 mg/L in $FeCl_3$ treatment in CF, COF, and SF effluent, respectively. The major removal of alkalinity was in the COF unit. This may be because of the necessity of alkalinity in forming hydroxide ions required for floc formation and precipitation. Around 0.45 mg/L alkalinity is required for 1.0 mg/L of alum for its complete hydrolysis into aluminium hydroxide (Metcalf & Eddy Inc. 2003). Hence, the drop in alkalinity was observed in COF effluent.

The effect of coagulants on turbidity and TSS is shown in Figures 9 and 10, respectively. Mean turbidity was reduced from 89.6 NTU to 52.7, 13.1, and 0.9 NTU in alum treatment; it was reduced from 83.8 NTU to 34.3, 3.6, and 0.6 NTU in PAC treatment; and from 77.7 NTU to 37.5, 10.0, and 2.3 NTU in $FeCl_3$ treatment in CF, COF, and SF effluent, respectively. Mean turbidity removal was 41.2, 85.4, and 99.0% in alum; 59.0, 95.6, and 99.3% in PAC; and 51.7, 87.1, and 97.0% in $FeCl_3$ treatment in CF,

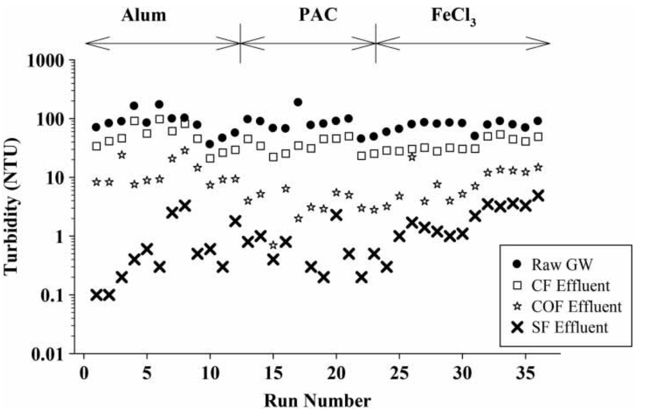

Figure 9 | Effect of coagulant on turbidity. CF, coarse sand filter; COF, coagulation/flocculation; SF, sand filter.

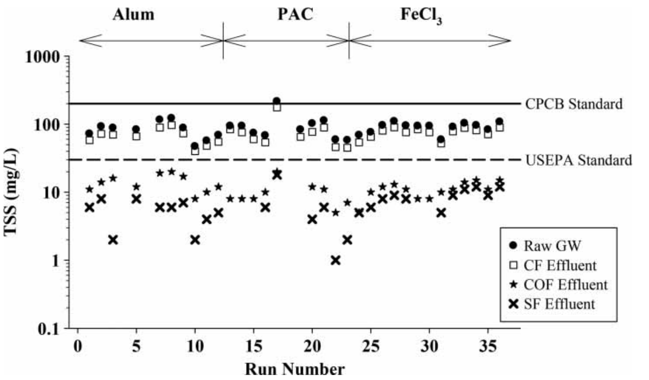

Figure 10 | Effect of coagulant on total suspended solids. CPCB (1993, 2008) standard: 200 mg/L max; USEPA (2004) standard: 30 mg/L max; CF, coarse sand filter; COF, coagulation/flocculation; SF, sand filter.

COF, and SF effluent, respectively. Mean TSS was reduced from 83 mg/L to 67, 14, and 5 mg/L in alum treatment; it was reduced from 93 mg/L to 75, 9, and 4 mg/L in PAC treatment; and from 92 mg/L to 78, 12, and 7 mg/L in $FeCl_3$ treatment in CF, COF, and SF effluent, respectively. Mean TSS removal was 19.2, 83.1, and 93.9% in alum; 19.3, 90.3, and 95.6% in PAC; and 15.2, 86.9, and 92.3% in $FeCl_3$ treatment in CF, COF, and SF effluent, respectively.

The effluent quality of all the three coagulation treatments was uniform, and turbidity removal was above 95% after filtration. In a similar study, Friedler & Alfiya (2010) observed turbidity levels drop from 46 NTU to 3.9 NTU (removal of 92%), and TSS levels from 70 mg/L to 4.4 mg/L (removal of 94%) while treating LGW using $FeCl_3$ at a dose of 22 mg-Fe/L. In the present study, similar turbidity and TSS removal was observed at a comparatively higher Fe dose (43.6 mg-Fe/L). The higher Fe dose needed in the present study may be due to more turbid raw GW, and rapid mixing by a pneumatic method as opposed to the mechanical mixing (i.e., rapid mixing at 60 rpm for 5 min, slow mixing at 30 rpm for 30 min) adopted by Friedler & Alfiya (2010).

Figure 11 shows the effect of coagulants on BOD_5. Mean BOD_5 was reduced from 95 mg/L to 86, 19, and 11 mg/L in alum treatment; from 113 mg/L to 101, 15, and 7 mg/L in PAC treatment; from 105 mg/L to 93, 23, and 15 mg/L in $FeCl_3$ treatment in CF, COF, and SF effluent, respectively. Mean BOD_5 removal was 9.5, 80, and 88.4% in alum treatment; 10.6, 86.5, and 93.5% in PAC treatment; and 11.4, 78.1, and 85.7% in $FeCl_3$ treatment in CF, COF, and SF effluent, respectively. Friedler & Alfiya (2010) observed BOD_5 removal from 103 mg/L to 44 mg/L (removal of 57%) using $FeCl_3$. Settling time after slow mixing was 40 min, and the effective sand size in the filter column was 0.585 mm. The higher BOD_5 removal observed in the present study may be due to the good coagulation efficiency achieved, higher settling time (≈2 h) after coagulation, and smaller effective sand size (0.25 mm) adopted in the sand filter as compared to those by Friedler & Alfiya (2010).

The mean FC count was reduced from 2.83×10^5 MPN/100 mL to 2.5×10^5, 6.5×10^4, 5.2×10^3 MPN/100 mL in alum treatment; from 2.0×10^5 MPN/100 mL to 1.4×10^5, 2.4×10^4, 9.8×10^2 MPN/100 mL in PAC treatment, from 3.0×10^5 MPN/100 mL to 2.6×10^5, 7.7×10^4, 5.5×10^3 MPN/100 mL in $FeCl_3$ treatment in CF, COF, and SF effluent, respectively.

The TC and FC count were <2 MPN/100 mL each, and the *E. coli* count was <2 CFU/100 mL after disinfection. FC

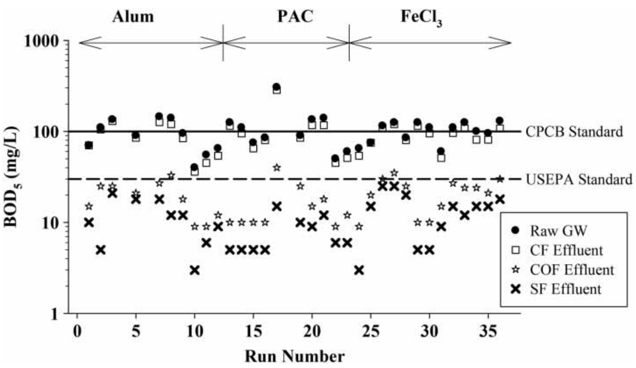

Figure 11 | Effect of coagulant on biochemical oxygen demand. CPCB (1993, 2008) standard: 100 mg/L max; USEPA (2004) standard: 30 mg/L max; CF, coarse sand filter; COF, coagulation/flocculation; SF, sand filter.

removal (log10) was 5.1, 4.35, and 5.11, in alum, PAC, and $FeCl_3$ treatment, respectively. Kariuki *et al.* (2011) observed FC removal from 1.1×10^3 to 0 MPN/100 mL (log10 removal = 3) using alum coagulation followed by disinfection using sodium hypochlorite (dose and contact time not reported). The higher FC removal observed in the present study may be due to the chlorine dosage applied and proper contact time provided.

Compliance of treated greywater with reuse standards

USEPA (2004) standards for restricted access area irrigation (RAI) prescribe pH = 6–9, TSS $\leq$ 30 mg/L, $BOD_5 \leq$ 30 mg/L, fecal coliforms $\leq$ 200 MPN/100 mL, chlorine (Cl_2) = 1 mg/L residual (minimum). Standards for construction (soil compaction, dust control, washing aggregate and making concrete) are the same as RAI. WHO (2006) standards for unrestricted irrigation of crops prescribe *E. coli* < 1,000 CFU/100 mL. CPCB (1993, 2008) standards for discharge into land for irrigation, and industrial cooling prescribe pH = 5.5–9.0, TSS < 200 mg/L, BOD_5 < 100 mg/L, O&G < 10 mg/L, arsenic < 0.2 mg/L, electrical conductivity < 2,250 µS/cm, sodium adsorption ratio (SAR) < 26, boron < 2 mg/L.

In the two-stage sand filtration study, treated mean greywater TSS, BOD_5, O&G, and EC_{25} were 15 mg/L, 28 mg/L, 8 mg/L, and 465 µS/cm, respectively. The median pH was 7.24. In alum-treated GW, the mean TSS, BOD_5, O&G, and EC_{25} were 5 mg/L, 11 mg/L, 1 mg/L, and 495 µS/cm, respectively. In PAC-treated GW, the mean TSS, BOD_5, O&G, and EC_{25} were 4 mg/L, 7 mg/L, 2 mg/L, and 518 µS/cm, respectively. In $FeCl_3$-treated GW, the mean TSS, BOD_5, O&G, and EC_{25} were 7 mg/L, 15 mg/L, 3 mg/L, and 522 µS/cm, respectively. Boron and arsenic were <0.01 mg/L. Residual chlorine was >1 mg/L in disinfected effluents from all the four treatment options. Hence, treated GW from all the four options satisfied standards for restricted access area irrigation, construction, and industrial cooling as per USEPA (2004), WHO (2006), and CPCB (1993, 2008) standards.

Comparison of treatment options using AHP

The hierarchy structure of the AHP model used in the present study is shown in Figure 12. Treatment cost (TRC), the ability of the treatment option to work robustly (AB), and compliance of treated GW with reuse standards (CS) were the main criteria of comparison. Reuse parameters prescribed in the reuse standards referred to were considered as sub-criteria of CS. CS criteria include the sub-criteria pH, turbidity (TUR), EC_{25}, TSS, O&G, BOD_5, boron, SAR, and FC. Concentrations of arsenic were the same (i.e., <0.01 mg/L) in raw as well as treated GW, so it was not included in CS for decision-making.

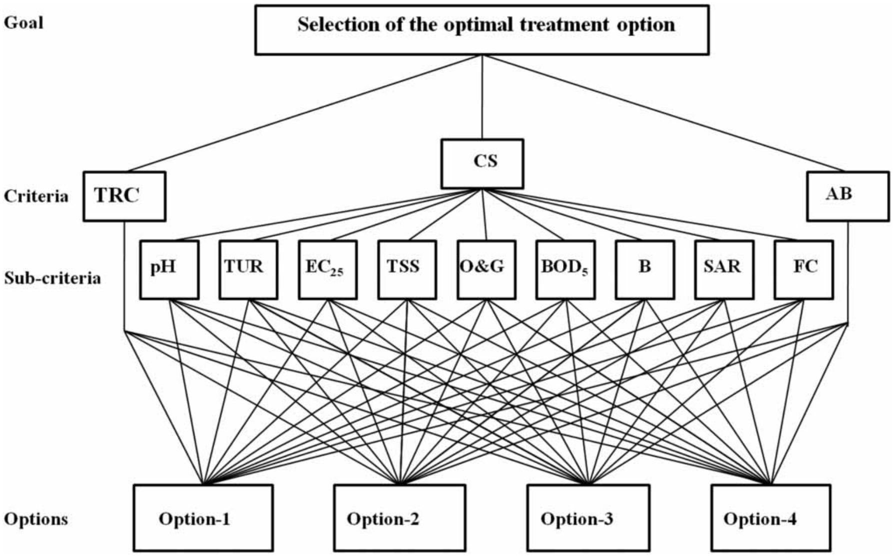

Figure 12 | Hierarchy structure of the AHP model used in the present study.

Pair-wise comparison matrix and criteria weights

The pair-wise comparisons find the relative importance of the criteria, which are rated by the nine-point scale as given in Table 2. Table 6 shows the pair-wise comparison matrix (Mat A1) and weights of the main criteria. Table 7 shows the pair-wise comparison matrix and local weights for sub-criteria of CS.

The consistency ratio, which is based on the consistency index, determines the acceptance of the weights. This is one of the essential checks in the AHP method which aims to eliminate the possibility of inconsistency in the criteria weights. The consistency of the judgment matrix was tested by calculation of the consistency index (*CI*) as Equation (6):

$$CI = \frac{\lambda \max - M}{M - 1} \tag{6}$$

where λmax is the maximum Eigen value of the matrix and could be calculated from the average of matrix A4 (refer to Table 6), and M is the order of the matrix (here, $\lambda max \approx 3$ and $M = 3$). In the present study, the exact values were used in comparing attributes in the relative importance matrix; therefore *CI* was zero.

The consistency ratio (*CR*) was calculated as Equation (7):

$$CR = \frac{CI}{RI} \tag{7}$$

where *RI* is the random index which depends upon the size of relative importance matrix. Here, for the main criteria, $CI \approx 0$ and $RI_3 = 0.52$ (Saaty 1980). Hence, $CR \approx 0$.

Saaty (1980) has suggested a $CR \leq 0.10$ for concluding the consistency of the pairwise matrix and validating the weights. Here, $CR \approx 0$ indicates that the matrix was consistent and the weights were valid.

Global priority weights

Since there were no sub-criteria in the TRC and AB their global priority weights (GPW) were as calculated in Table 6. Criterion CS has sub-criteria, and needs conversion of weights obtained in Table 7 by multiplying their criteria weight. Table 8 presents all the criteria and their global priority weights.

Comparison of reuse options on basis of effluent quality

The performance of a system can be evaluated from the quality of effluent produced by it. Reuse standards specify the limits of parameters which are mostly quantitative. In the present scenario, while comparing two options, the option producing the effluent having the lowest concentration of parameters (except pH) can be regarded as better than the other one. However, this comparison may be biased if both the options compared were not fed with the same raw wastewater. In such situations, when the raw wastewater quality is different in each option, comparison of the options based on the removal of the parameters (% removal or log removal) may be a better approach. In the present study, the treatment options were compared by both ways for the study purpose.

Greywater reuse options and criteria

The greywater reuse options and criteria used in decision-making are presented in Table 9. Treatment cost (TRC) indicates the cost of treatment of GW per million liters/d (MLD) flow. Treatment cost is a theoretical estimation that includes

Table 6 | Pair-wise comparison matrix and weights of the main criteria

	Mat A1				Mat A2	Mat A3	Mat A4
	TRC	AB	CS	Geometric mean	Weight	= A1*A2	= A3/A2
TRC	1.000	0.857	0.667	0.830	0.273	0.818	2.997
AB	1.200	1.000	0.778	0.968	0.318	0.955	3.002
CS	1.500	1.286	1.000	1.245	0.409	1.227	3.001

Mat, matrix.

Table 7 | Pair-wise comparison matrix and local weights for sub-criteria of CS

	pH	TUR	EC_{25}	TSS	O&G	BOD_5	Boron	SAR	ΔFC	Weight
pH	1.000	1.400	1.750	1.167	1.167	1.000	1.400	1.400	1.000	0.135
TUR	0.714	1.000	1.250	0.833	0.833	0.714	1.000	1.000	0.714	0.096
EC_{25}	0.571	0.800	1.000	0.667	0.667	0.571	0.800	0.800	0.571	0.077
TSS	0.857	1.200	1.500	1.000	1.000	0.857	1.200	1.200	0.857	0.115
O&G	0.857	1.200	1.500	1.000	1.000	0.857	1.200	1.200	0.857	0.115
BOD_5	1.000	1.400	1.750	1.167	1.167	1.000	1.400	1.400	1.000	0.135
Boron	0.714	1.000	1.250	0.833	0.833	0.714	1.000	1.000	0.714	0.096
SAR	0.714	1.000	1.250	0.833	0.833	0.714	1.000	1.000	0.714	0.096
FC	1.000	1.400	1.750	1.167	1.167	1.000	1.400	1.400	1.000	0.135

$\lambda max \approx 9$, $M = 9$; $CI \approx 0$; $RI_9 = 1.45$ (Saaty 1980); $CR \approx 0$.

Table 8 | Global priority weights of criteria and sub-criteria

Criteria	TRC	AB	CS								
Sub-criteria			pH	TUR	EC_{25}	TSS	O&G	BOD_5	Boron	SAR	FC
GPW	0.273	0.318	0.055	0.039	0.031	0.048	0.048	0.055	0.039	0.039	0.055

Table 9 | Greywater reuse options and criteria used for comparison using AHP

Option	TRC US$/MLD	AB –	ΔpH –	TUR NTU	EC_{25} µS/cm	TSS mg/L	O&G mg/L	BOD_5 mg/L	Boron mg/L	SAR –	FC $Log^{\#}_{10}$
Option 1	532	4.0	0.24	4.5	465	15	8	28	0.01	2.00	0.301
Option 2	9,249	6.0	0.44	0.9	495	5	1	11	0.01	1.50	0.301
Option 3	9,897	7.5	0.37	0.6	520	4	2	7	0.01	2.35	0.301
Option 4	3,703	7.0	0.54	2.3	523	7	3	15	0.01	2.15	0.301

$^{\#}$ MPN/100 mL.

cost of construction, chemicals, energy, and manpower on an annualized basis. Treatment units were designed for a flow of 240 L/d, keeping in view the test conditions in the present study, and the TRC was worked out. Further, the TRC was converted to per MLD flow.

The ability of the treatment option to work robustly (AB) is a qualitative term. The qualitative judgments on AB were made and were transformed to crisp numbers between 1 and 9 using Saaty's scale (see Table 2). Average optimum doses of $FeCl_3$ and PAC required were less than the alum dose (Ghaitidak & Yadav 2014). Less coagulant dose leads to a low cost of handling and less sludge production. Therefore, $FeCl_3$ and PAC were rated slightly higher than alum. PAC can work better on a wide range of pH compared to $FeCl_3$, hence the rating of PAC was kept slightly higher than that of $FeCl_3$. Any variation in the GW quality can be easily tackled by adjusting the coagulant dose, hence the AB rating of option 2 to 4 was higher than that of option 1.

Criteria CS included pH, turbidity (TUR), EC_{25}, TSS, O&G, BOD_5, boron, SAR, and FC. Sub-criterion pH was transformed to ΔpH as Equation (8):

$$\Delta \mathrm{pH} = ((7 - pH)^2)^{0.5} \tag{8}$$

pH is a reuse standard that is preferred to be neither a minimum nor maximum. All the referred standards prescribe a range, that is, 6–9 (USEPA 2004); 5.5–9 (CPCB 1993, 2008). Basically, the pH of water varies from 0 to 14. Water at pH 7 is neutral. Therefore, Equation (8) measures the deviation of pH from 7 (which gives it a non-negative value). With this transformation, the criterion pH was renamed ΔpH.

Normalization of the data

When the dimensions of the criteria are different, normalization of the data is required. Normalization is the process of bringing all the criteria to a comparable platform by making them dimensionless. Table 10 presents normalized data of criteria mentioned in Table 9. Criterion AB was beneficial and all other criteria/sub-criteria were non-beneficial. Beneficial criteria were the cases of maximization and the non-beneficial criteria were the cases of minimization. Normalized values of a beneficial criterion were obtained by dividing each element of the criterion in the decision table by its largest element. In the case of non-beneficial criteria, the reciprocal of each element of the criterion in the decision table was multiplied by its smallest element.

Selection index and ranking of options

In overall comparison (i.e., considering criteria TRC, AB, and CS), option 1 (TSF) was the optimal option with the highest SI (see Table 11). Option 3 (PAC treatment), option 2 (alum treatment), and option 4 ($FeCl_3$ treatment) were ranked as 2, 3, and 4, respectively. Finally, the selection string was option 1–3–2–4. Considering only the criterion of CS, the optimal option was option 3 (PAC coagulation). This indicates that the PAC coagulation produced the best quality effluent. The selection string was option 3–2–4–1.

Comparison of reuse options on the basis of removal of parameters

Greywater reuse options and criteria

Treatment cost (TRC) and the ability of the treatment option to work robustly (AB) were the same as previously. The removals of parameters were calculated referring to the mean GW characteristics in Table 5. Greywater reuse options and criteria used in comparison using the AHP, on the basis of removal efficiency, are given in Table 12.

The sub-criterion pH was transformed to ΔpH using Equation (8). The percentage removal (%R) of parameters TUR, EC_{25}, TSS, O&G, BOD_5, boron, and SAR were calculated as Equation (9):

$$\%R = (C_R - C_T)x100/C_R \tag{9}$$

where C_R = concentration of the parameter in raw GW; C_T = concentration of the parameter in treated GW.

Removal of parameter FC was calculated using Equation (10):

$$\Delta FC = Log_{10}(FC_i) - Log_{10}(FC_e) \tag{10}$$

where ΔFC = log removal; FC_i = FC count in raw GW (MPN/100 mL); FC_e = FC count in treated GW (MPN/100 mL).

Normalization of the data

TRC and ΔpH were non-beneficial criteria, and all other criteria/sub-criteria were beneficial. Non-beneficial criteria were the cases of minimization, and beneficial criteria were the cases of maximization. Data were normalized as mentioned earlier.

Table 10 | Normalization of the data

Option	TRC	AB	ΔpH	TUR	EC_{25}	TSS	O&G	BOD_5	Boron	SAR	FC
Option 1	1.00	0.53	1.00	0.14	1.0	0.28	0.13	0.26	1.00	0.75	1.00
Option 2	0.06	0.80	0.55	0.68	0.94	0.84	1.00	0.67	1.00	1.00	1.00
Option 3	0.05	1.00	0.65	1.00	0.89	1.00	0.48	1.00	1.00	0.64	1.00
Option 4	0.14	0.93	0.44	0.27	0.89	0.60	0.33	0.49	1.00	0.70	1.00

Table 11 | Selection index and ranking of the options on the basis of effluent quality

Option	Criteria (TRC + AB + CS) SI	Criteria (TRC + AB + CS) Rank	Criterion (CS) SI	Criterion (CS) Rank
Option 1 (TSF)	0.692	1	0.610	4
Option 2 (alum treatment, alum dose 416 ± 44 mg/L)	0.613	3	0.839	2
Option 3 (PAC treatment, PAC dose 279 ± 40 mg/L)	0.680	2	0.849	1
Option 4 ($FeCl_3$ treatment, $FeCl_3$ dose 141 ± 12 mg/L)	0.591	4	0.625	3

Selection index and ranking of options

In overall comparison (i.e., considering the criteria of TRC, AB, and CS), option 1 obtained the highest SI (see Table 13). Option 1 (TSF) was the best management option, on the basis of removal of parameters, for treating GW compared to the other three options in the present study. Option 3 (PAC treatment), option 4 ($FeCl_3$ treatment), and option 2 (alum treatment) were ranked 2, 3, and 4, respectively. Finally, the selection string was option 1–3–4–2. Considering only criterion CS the selection string was the same as the overall comparison (i.e., option 1–3–4–2).

CONCLUSIONS

Around 250 L GW was treated per day on-site. The findings of the study can be useful for treatment of GW on a household basis. In the two-stage sand filtration study, treated mean greywater TSS, BOD_5, O&G, and EC_{25} were 15 mg/L, 28 mg/L, 8 mg/L, and 465 μS/cm, respectively. The median pH was 7.24. In alum-treated GW, the mean TSS, BOD_5, O&G, and EC_{25} were 5 mg/L, 11 mg/L, 1 mg/L, and 495 μS/cm, respectively. In PAC-treated GW the mean TSS, BOD_5, O&G, and EC_{25} were 4 mg/L, 7 mg/L, 2 mg/L, and 518 μS/cm, respectively. In $FeCl_3$-treated GW, the mean TSS, BOD_5, O&G, and EC_{25} were 7 mg/L, 15 mg/L, 3 mg/L, and 522 μS/cm, respectively. Boron and arsenic were <0.01 mg/L. Residual chlorine was >1 mg/L in all the tested effluents. Fecal coliforms were <2 MPN/100 mL and *E. coli* <2 CFU/100 mL after chlorination (contact time 30 min). Hence, treated GW from all the four options satisfied standards for restricted access area irrigation, construction, and industrial cooling as per USEPA (2004), WHO (2006), and CPCB (1993, 2008) standards.

The study provides a step-by-step solution for ranking of options using the AHP. The options thus ranked can be useful for choosing appropriate technology for GW reuse. Comparison of the options on the basis of effluent quality resulted in TSF being the optimal option. PAC treatment, alum treatment, and $FeCl_3$ treatment were ranked as 2, 3, and 4, respectively. Comparison on the basis of removal of parameters resulted in TSF being the optimal option. PAC treatment, $FeCl_3$ treatment, and alum treatment were ranked as 2, 3, and 4, respectively.

In two-stage sand filtration, the regeneration of filters at 30–40 days' intervals may be a major limitation for implementation of this study. The operational aspect also needs close supervision of flow rates, application of coagulant dose, cleaning of screening mesh, and cleaning of the mini coarse sand filter on a daily basis. Investigations on GW from different sources such as kitchen and laundry; testing of filters with variable effective sand size and depth; and application of different multi-criteria techniques, e.g., TOPSIS, fuzzy AHP, etc., for prioritizing the options may be a further scope of research.

Table 12 | Greywater reuse options and criteria used in comparison using AHP

Option	TRC US$/MLD	AB –	ΔpH –	TUR %	EC_{25} %	TSS %	O&G %	BOD_5 %	Boron %	SAR %	ΔFC log_{10}
Option 1	532	4.0	0.24	94.60	4.71	83.70	77.14	73.58	85.90	15.25	4.99
Option 2	9,249	6.0	0.44	99.00	– 9.03	93.98	96.67	88.42	84.10	03.23	5.10
Option 3	9,897	7.5	0.37	99.27	– 4.97	95.53	93.26	93.49	87.30	24.19	4.85
Option 4	3,703	7.0	0.54	97.04	– 4.40	92.39	90.32	85.71	85.70	12.24	5.11

Table 13 | Selection index and ranking of the option on the basis of removal of parameters

	Criteria (TRC + AB + CS)		Criteria (CS)	
Option	**SI**	**Rank**	**SI**	**Rank**
Option 1 (TSF)	0.806	1	0.889	1
Option 2 (alum treatment, alum dose 416 ± 44 mg/L)	0.522	4	0.617	4
Option 3 (PAC treatment, PAC dose 279 ± 40 mg/L)	0.652	2	0.783	2
Option 4 ($FeCl_3$ treatment, $FeCl_3$ dose 141 ± 12 mg/L)	0.623	3	0.702	3

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