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AN INVESTIGATION ON GREYWATER TREATMENT OPTIONS FOR REUSE: RANKING BY ANALYTIC HIERARCHY PROCESS

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Abstract

The objective of the present study was to (i) compare different treatment options for greywater (GW) reuse, (ii) assess the potential of treated GW for reuse, and (iii) select the optimal treatment option by using Analytic Hierarchy Process (AHP). Raw GW was settled for 2 h. Five different treatment options were investigated simultaneously in parallel using the same influent (settled GW). The treatment options were (1) sand filtration, (2) sand/brick bat filtration, (3) alum coagulation/flocculation (COF), (4) polyaluminium chloride COF, and (5) ferric chloride COF as the main treatment. Almost all the treatment options examined could produce GW quality suitable for reuse in restricted access area irrigation, construction, and industrial cooling. The mean biochemical oxygen demand (BOD_5) varied from 15-33 mg/L, and total suspended solids (TSS) varied from 11-26 mg/L after treatment.

The treatment options were ranked using AHP. Three main criteria (1) compliance of treated GW with reuse standards (CS), (2) treatment cost, and (3) ability of treatment option to work robustly were selected in the present study. Criteria for CS was further divided into sub criteria, which include the reuse parameters pH, turbidity, electrical conductivity, TSS, oil and grease, BOD_5,ammonia nitrogen, and sodium adsorption ratio. Considering compliance to CS, the selection string was option 4-5-1-3-2. Whereas, considering all the attributes, the selection string was option 5-4-3-1-2. This article gives an insight on investigation (comparative study) of GW reuse options and a scientific way for their ranking.

*Key words:*analytic hierarchy process, greywater, ranking, reuse, treatment options

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1. Introduction

Greywater (GW) is wastewater from kitchen, bath, and laundry, excluding wastewater from toilets (Bodnar et al., 2014; Gross et al., 2007; WHO, 2006). Light greywater (LGW) is the GW from bathroom, showers, tubs, and clothes washing machines 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 and Yadav, 2013). Hence, GW reuse can be an effective measure for saving water on the domestic level and reducing load on wastewater treatment plant. The reuse of GW for nonportable water applications is a potential solution for water-deprived regions worldwide. GW is not suitable for direct use but can be useful for nonportable reuse such as irrigation and toilet flushing (Gross et al., 2007).

At present, a limited number of studies are reported on LGW using sand filters (Al-Zou'by et al., 2017; Dalahmeh et al., 2014; Gross et al., 2007, 2008). Gross et al. (2008) treated GW using a commercial unit comprising sand filtration and electrolysis. Gross et al. (2007) and Dalahmeh et al. (2014) examined

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*Author to whom all correspondence should be addressed: e-mail: dmghaitidak@gmail.com; Phone: +91 9890874385 sand filters using artificial/synthetic GW. Present literature (except Al-Hamaiedeh and Bino, 2010) lacks investigations on the performance of sand filters with respect to a complete set of reuse parameters prescribed in the national or international standards for a particular reuse (urban reuse, irrigation, construction etc.). However, filtration unit tested by Al-Hamaiedeh and Bino (2010) satisfied Jordanian irrigation standards but could not satisfy irrigation standards of USEPA (2004) and WHO (2006). In India, Mandal et al. (2011) tested LGW using filtration followed by aeration and disinfection for a duration of 2 months. The study lacks in reporting some reuse parameters (residual chlorine, sodium adsorption ratio, arsenic etc.) prescribed by USEPA (2004) and CPCB (1993; 2008). Vakil et al. (2014) tested GW at laboratory scale from an Indian middle-class household using electrocoagulation. Parameters monitored after treatment were COD, turbidity, and TC (see Table 1 for abbreviations). This study was reported without targeting any particular reuse of GW. Hence, there is immense scope for evaluating the performance of sand filters as well as coagulants and verifying the suitability of treated GW for a particular reuse.

Although the alum (polyaluminium chloride, PAC), and ferric chloride ($FeCl_3$) coagulants are used in water and sewage treatment, investigations particularly on LGW by using these coagulants are quite limited. Performance of PAC in treating GW is not documented so far (Abu Ghunmi et al., 2011a; Ghaitidak and Yadav, 2013). Since GW significantly differs from sewage, the investigation on GW using coagulants is a point for research. Moreover, in a developing/low income country such as India, research on GW is not so common. The present literature lacks the study of coagulants with respect to evaluating optimum coagulant dosage and assessing the potential of treated GW for a particular reuse (Antonopoulou et al., 2013; Kariuki et al., 2011; Skudi et al., 2011). Moreover, cited documentation did not include reuse parameters that is, TSS, O&G, BOD_5, COD (Skudi et al., 2011); turbidity, TSS, BOD_5, COD, E. coli (Kariuki, 2011); turbidity, O&G, BOD_5, FC, E. coli (Antonopoulou et al., 2013). Present literature, also, has no comparative study among filtration and coagulation/flocculation treatments.

The Analytic Hierarchy Process (AHP) is a well-known multiple criteria decision-making method that has been widely applied to solve problems in many fields (Ishizaka and Labib, 2011) and specifically for solid waste management (Karmperis et al., 2012; 2013). Presently, applications of multiple attribute decision making to GW investigations are quite limited. Chen et al. (2012) applied preference ranking organization method for enrichment evaluation for selecting recycling alternative in a household laundry in Sydney. No study using AHP on the management of LGW is reported so far. The present study gives a step-by-step procedure to the use of AHP for selecting the optimal alternative in LGW investigations. In view of the above, the objective of the present study was to (i) compare different treatment options for GW reuse, (ii) assess the potential of treated GW for reuse, and (iii) select the optimal treatment option by using AHP.

2. Material and methods

2.1. Greywater source

Greywater was collected from a student hostel of capacity 474 located at Sardar Vallabhbhai National Institute of Technology (SVNIT), Surat, India. The GW collection pipe was cut and GW was diverted to the collecting tank (CT). GW was homogeneously mixed in the CT prior to collection of samples. Samples were collected at around 10 am; approximately 80 l of GW was collected for the experimental purpose and the remaining was discarded. Before use, the CT was washed each time with clean potable water to avoid any carryover of contaminants. The experiments were started within 30 to 45 min from the time of collection of GW. Duration of the study was from June 2013 to December 2013.

2.2. Analytical procedures

Parameters analyzed were pH, turbidity, temperature, EC_{25}, total solids, TDS, TSS, alkalinity, O&G, BOD_5, COD, NH_3-N, chlorides, PO_4-P, sulfates, NO_3-N, TC, FC, E.coli, SAR, boron, and arsenic.

Table 1. List of abbreviations

Abbreviation	*Meaning*	*Abbreviation*	*Meaning*
Avg	Arithmetic average	NO_3-N	Nitrates
BOD_5	Biochemical oxygen demand	NS	Number of samples
BT	Bath	O&G	Oil and grease
Cl_2	Chlorination	OD	Optimum dose
COD	Chemical oxygen demand	OP	Option
COF	Coagulation/flocculation	PO_4-P	Phosphates
E. coli	Escherichia coli	PST	Plain settling
EC_{25}	Electrical conductivity	SAR	Sodium adsorption ratio
F1	Filter 1	SD	Standard deviation
F2	Filter 2	SH	Shower
FC	Fecal coliforms	TDS	Total dissolved solids
Mat	Matrix	TSS	Total suspended solids
NH_3-N	Ammonia nitrogen	WB	Wash basin

The 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 EC_{25} was measured using a digital conductivity meter (Systronics-Conductivity TDS Meter 308). All the parameters were analyzed as per standard methods (APHA, 2005). Reagent/laboratory grade chemicals were used in the study.

2.3. Greywater treatment options

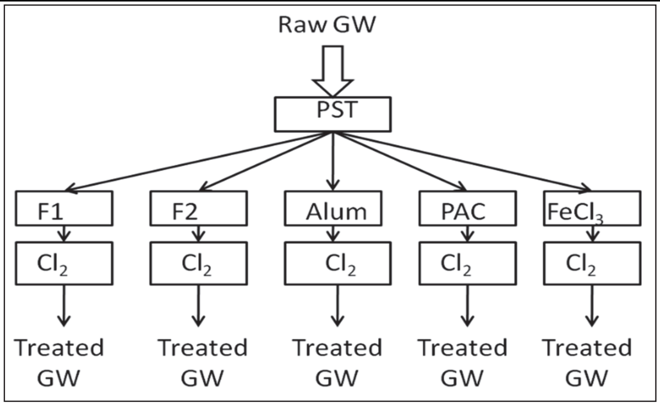
Five different treatment options were examined in the present study as shown in Fig. 1. The first two options were based on sand/brick bat filtration and the next three options include alum, PAC, and $FeCl_3$ coagulation/flocculation as the main treatment.

2.3.1. Greywater settling

A plastic tank with base 71cm x 71cm and height 38 cm was used for settling of the GW. GW was settled in a settling tank for 2 h and the settled GW was used in all the five treatment options.

2.3.2. Greywater filtration

A plastic drum of internal diameter 43 cm and internal height 72 cm having volume 104 l was used to prepare the sand filter. Fig. 2 shows the schematic diagram of the sand filter used in this study. F1 comprised mainly locally available sand and F2 comprised sand and brickbats. The details of the media used in F1 and F2 are presented in Table 2.



Option 1: Raw GW-PST-F1-Cl_2-Treated GW;
Option 2: Raw GW-PST-F2- Cl_2-Treated GW;
Option 3: Raw GW-PST-Alum COF- Cl_2-Treated GW;
Option 4: Raw GW-PST-PAC COF- Cl_2-Treated GW;
Option 5: Raw GW-PST-$FeCl_3$ COF- Cl_2-Treated GW

Fig. 1. Greywater treatment options examined

Table 2. Details of media used in filter

Layer	*Media and size (mm)*	*F1*	*F2*
		Depth(cm)	*Depth(cm)*
Free board	-	48-72	48.1-72
Standing water	-	42-48	44- 48.1
Layer-III	Fine sand (0.125-1)	14-42	16-44
Layer-II	Medium sand (1-2)	10-14	12.5-16
Layer-I	Coarse Sand (2-4.75)	0-10	--
	Brick bats (12)	--	0-12.5

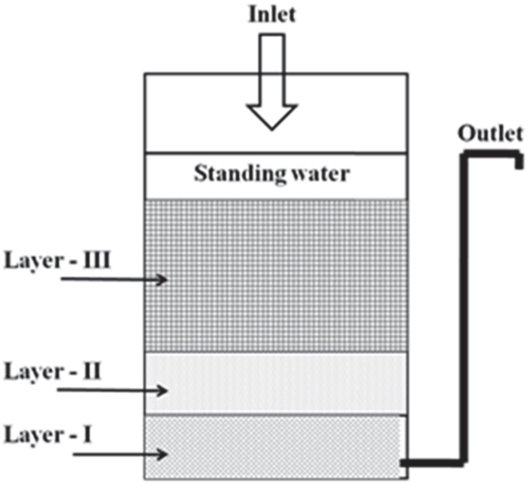


Fig. 2. Schematic diagram of filter

The effective sand size of fine sand was 0.4 mm. The uniformity coefficient was 2. Initial pore volume of F1 was 24% and that of F2 was 29%. Around 20 l of settled GW was charged in each filter and was retained for 24 h. A plastic bucket with small holes at the bottom was used as a diffuser to gradually feed the GW to the filter. The effluent was collected next day.

2.3.3. Greywater coagulation/flocculation

Alum ($Al_2(SO_4)_3$ $18H_2O$), PAC, and $FeCl_3$ were used in the study. Alum contained 4.75% Al, PAC contained 15.07% Al, and $FeCl_3$ contained 30.97% Fe by weight. Settled GW used in these experiments was same as used for feeding F1 and F2.

A six-paddle stirrer jar test apparatus was used in GW coagulation/flocculation. A rapid mixing at 120 rpm for 90 s and slow mixing at 30 rpm for 15 min was adopted. The flocs formed in the jars were allowed to settle for the next 30 min. The dose corresponding to the least turbidity was considered OD. Next, the supernatant from the jar corresponding to the OD were collected and were analyzed within 2 to 24 h (except the analysis of metals and ground elements). The entire jar test was repeated if an OD did not appear.

2.3.4. Disinfection of treated greywater

Bleaching powder (BP) was used for disinfection of GW. 1 g BP was dissolved in 1000 mL distilled water (1 mL of the stock = 1 mg of BP). Available chlorine in BP was 22% by weight. The chlorine dose was added to the treated GW and residual chlorine was measured after 30 min contact time. The same disinfected samples were used for microbial analysis.

2.4. Statistical analysis

The results were analyzed using descriptive and multivariate statistics using Excel 2007 and SYSTAT (Sigmaplot 10). A paired t-Test (paired two sample for means) was performed on parameters monitored before and after the treatment. This test wasappropriatein the present study because the compared parameters before and after the treatment were of same size, and parameters compared were acontinuous variable.

The null (H_0) and alternate hypothesis (H_1) framed in t-Test were as (Eqs. 1-2):

$$H_0: \mu_R = \mu_T \tag{1}$$

$$H_1: \mu_R \neq \mu_T \tag{2}$$

where:μ_R and μ_T are mean concentrations of parameters (attributes) in raw and treated GW, respectively; μ_T can be replaced subsequently as μ_1,μ_2, μ_3,μ_4, and μ_5, which corresponds to option 1, option 2, option 3, option 4, and option 5, respectively.

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

2.5. Analytic Hierarchy Process

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 way of finding the maximum Eigen value, and reduction in inconsistency of judgments. The main steps in AHP are as follows (Saaty, 1980; Rao, 2007):

Step 1: The first step is to determine the goal, criteria/subcriteria, and alternatives in decision making. The criteria are often termed as attributes. A quantitative or qualitative value may be assigned to each identified attribute.

Step 2: In this step, all the information available on attributes and alternatives is arranged in a matrix form, which is commonly termed as decision table "D". A decision table with "m" alternatives and "n" attributes is presented in Table 3. The decision table shows alternatives A_i (where i = 1 to m), attributes C_j (where j=1 to n), priority weights of attributes W_j (where j=1, 2,…, n), and measures of performance of alternatives d_{ij}. Therefore, an element d_{ij} of the decision matrix "D" gives the original actual values of the jth attribute with its units for the ith alternative.

Table 3. General format of the decision table (D)

Alternatives	***Criteria/Attributes***					
	C_1	***C_2***	***C_3***	-	-	***C_n***
	(W_1)	***(W_2)***	***(W_3)***	-	-	***(W_n)***
A_1	d_{11}	d_{12}	d_{13}	-	-	d_{1n}
A_2	d_{21}	d_{22}	d_{23}	-	-	d_{2n}
A_3	d_{31}	d_{32}	d_{33}	-	-	d_{3n}
-	-	-	-	-	-	-
-	-	-	-	-	-	-
A_m	d_{m1}	d_{m2}	d_{m3}	-	-	d_{mn}

For the region four different classes: good rangeland quality, poor rangeland quality, orchard, and residential classes (Anderson *et al.,* 1976) were defined using 7, 4 and one bands (Figs. 2-4). If the vegetation cover was ≥ 60%, it was classified as good rangeland quality and when the vegetation cover < 60% was classified as poor rangeland quality, although the vegetation within the area is sparse, but most important for its wild life. The overall accuracy was 82.60% for the image concerning the year 1984, 87.29% for 2000 and 96.73% for 2010, respectively (Table 2). The kappa coefficient was also quite high.

Step 3: In this step, a pairwise comparison matrix of relative importance (e.g., A1) is constructed. In the matrix, $c_{ij}=1$ when i=j, and $c_{ji}=1/c_{ij}$ (Eq. 3).

$$C_{nxn} = \begin{array}{c} \text{Attributes} \\ C_1 \\ C_2 \\ C_3 \\ \cdots \\ \cdots \\ C_n \end{array} \begin{bmatrix} C_1 & C_2 & C_3 & \cdots & \cdots & C_n \\ c_{11} & c_{12} & c_{13} & \cdots & \cdots & c_{1n} \\ c_{21} & c_{22} & c_{23} & \cdots & \cdots & c_{2n} \\ c_{31} & c_{32} & c_{33} & \cdots & \cdots & c_{3n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ c_{n1} & c_{n2} & c_{n3} & \cdots & \cdots & c_{nn} \end{bmatrix} \qquad (3)$$

For deciding the importance of the attributes, an expert opinion survey was conducted. Table 4 presents the comparison scale used in AHP for the expert opinion survey in the present study. A questionnaire containing the list of the attributes was circulated among five environmental experts and their responses regarding the importance to be assigned to the attributes were collected in the linguistic format. The linguistic variables were converted to absolute numbers.

The average of the responses of all the five experts was considered for forming the relative importance matrix. Because this study was related to the environmental issues, experts from the environmental field were selected. Experts were academicians and professionals.

Step 4: In this step, the priority weights are found. Let us denote the W_j matrix as A2. The priority weight of the attribute is calculated by geometric mean (GM) of the ith row and by normalizing the GM of the row in the comparison matrix as (Eqs. 3 and 4).

$$GM_i = \left[\prod_{j=1}^{n} c_{ij}\right]^{\frac{1}{n}} \qquad (3)$$

$$W_j = GM_i / \sum_{i=1}^{n} GM_i \qquad (4)$$

Step 5: In this step, the maximum Eigen value is calculated. The matrices are calculated such that A3=A1×A2 and A4=A3/A2. Next, the maximum Eigen value (λ_{max})that is the average of matrix A4 is determined.

Step 6: The consistency ratio (CR) determines the acceptance of the weights. This is one of the essential verifications in the AHP method, which aims to eliminate the possibility of inconsistency in the attribute weights. The consistency of the judgment matrix is tested by calculating the consistency index (CI) and the CR as (Eqs. 5-6).

$$CI = (\lambda_{max} - M)/(M - 1) \qquad (5)$$

$$CR = CI/RI \qquad (6)$$

Saaty (1980) suggested CR≤0.10 for indicating the consistency of the pairwise matrix and for validating the weights. Random index (RI) depends upon the size of relative importance matrix (M).

Step 7: In this step, normalized values of the attributes in each alternative are obtained. Normalized value of the beneficial attribute is obtained by dividing each element in the decision table by its largest element. In the case of nonbeneficial attribute, the reciprocal of each element in the decision table is multiplied by its smallest element.

Step 8: The selection index (SI) for the alternatives are obtained by multiplying the weight (W_j) of each attribute with its corresponding normalized value for each alternative in the normalized data matrix, and summing all the attributes for each alternative. The alternatives are arranged in the descending order of the SI; the first rank is assigned to the alternative with the highest SI, second rank is assigned to the alternative with the second highest SI, and so forth, with rank m for the alternative with lowest SI.

3. Results and discussion

3.1. Characteristics of raw greywater

Characteristics of the raw GW analyzed in the present study are presented in Table 5. Most of the characteristics levels observed in the present study are in the range cited in the literature.

Table 4. The comparison scale used in AHP (Saaty, 1990)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 favor one activity over another	Low
4	II between 3 and 5	--	Below average
5	Strong importance	Judgment strongly favor 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
Reciprocals of the above nonzero- If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.			

In the present study, BOD_5 and COD ranged from 60 to 300 mg//L, and 176 to 540 mg/L, respectively; and BOD_5 /COD ratio varied from 0.34 to 0.56. In the literature reported, BOD_5 /COD ratio varied from 0.34 to 0.75 for bath, 0.35 to 0.65 for a shower, and 0.27 to 0.53 in case of washbasin GW (Friedler, 2004; Jefferson et al., 2004). Abu Ghunmi et al. (2011b) reported a BOD_5/COD ratio as 0.42 for combined bath, laundry, and washbasin GW. Wastewater with BOD_5/COD ratio below 0.5 is not easily treatable by biological means. In addition, wastewater with BOD_5/COD ratio below 0.3 is not treatable by biological means, may contain toxic components and needs acclimatization of microorganisms (Metcalf and Eddy, 2003). In the present study, the mean BOD_5/COD ratio was 0.41.

Biological process needs a minimum BOD_5:N:P ratio of 100:5:1 for complete BOD_5 removal under aerobic conditions (Metcalf and Eddy, 2003). As GW does not include urine, it is expected to be deficient in nitrogen. Similarly, most of the phosphorus originates from detergents used in washing and is present only if laundry GW is included (Jefferson et al., 2004). Biological treatment can be used efficiently for collective wastewater treatment under supervision of trained staff, but it would be difficult to treat GW in single households where the inhabitants have no specific skills to treat wastewater (Antonopoulou et al., 2013). Thus, low BOD_5/COD ratio, and nutrient deficiency of the GW indicate enough scope for physicochemical (coagulation/flocculation) and biophysical (sand filtration) treatment in the present study.

3.2. Effect of settling on greywater characteristics

Fig. 3 shows the effect of settling on GW characteristics TSS, O&G, BOD_5, and COD. The level of pH, EC_{25}, SAR, and Boron in settled GW were 7.46±0.27, 566±101 µS/cm, 2.81±3.07, and 0.1±0.04 mg/L, respectively.

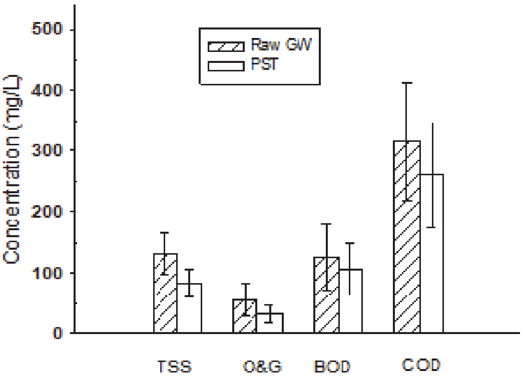


Fig. 3. Effect of settling on greywater characteristics

3.3. Greywater treatment using filtration

Both the filters were operated in two runs. The first run was from day 1 to day 42. The filter was regenerated by scrapping the top 10 cm layer and refilling by the same material after washing and drying. Around 50 L of clean potable water was poured in each filter and was drained through the bottom drain valve of the filter. The next run was from day 48 to day 130.

Table 5. Raw greywater characteristics

Parameter	***Present Study***			***Literature Data***		
	NS	***Range***	***Avg±SD***	***Australia^{a}***	***France^{b}***	***Israel^{c,d}***
GW Sources		BT,SH,WB	BT,SH,WB	BT	BT,SH,WB	BT,SH,WB
pH	22	6.9- 7.96	7.51±0.3	6.4-8.1	7.34-7.71	7-7.43
Turbidity (NTU)	22	32-148	94.6±31	60-240	35.3-462	
Temperature (^{0}C)	14	26.7-28.5	28±1			
EC_{25} (µS/cm)	14	410-793	588±117	82-250	358-627	1130
Total Solids (mg/L)	22	364-628	492±83			770-1090
TDS (mg/L)	22	226-464	361±70			
TSS (mg/L)	22	76-208	131±34	48-120	37-360.5	78-303
Alkalinity(mg/L)	22	68-220	145±41	24-43		
O&G (mg/L)	11	24-102	52±24	37-78		7.2-164
BOD_5 (mg/L)	15	80-300	127±58	76-200	78-670	44-424
COD (mg/L)	14	184-540	314±93		100-795	230-645
NH_3-N(mg/L)	9	1.1-3.4	2.49±0.7	<0.1-15		0.39-1.2
Chlorides(mg/L)	10	25-308	75±84			
PO_4-P (mg/L)	8	0.46-1.2	0.71±0.3			4.56-15
Sulphates (mg/L)	7	5.2-22	14.2±7.13			
NO_3-N (mg/L)	7	0.94-4.41	1.52±0.61			
TC (MPN/100 mL)	7	3.5E5–9.2E6	3.5E6±2.5E6	500-2.4E7	4.9E6-4.7E9	
FC (MPN/100 mL)	7	1.7E3–2.1E4	1.4E4±1.0E4	170-3.3E3	2.3E4-2.0E6	3.5E3-4E6
E.coli (cfu/100 mL)	7	150-1400	750±626			
SAR	5	1.18-1.98	1.54±0.31			
Boron (mg/L)	5	0.051-0.168	0.09±0.05			0.31-0.44
Arsenic (mg/L)	5	<0.01	<0.01			

Greywater characteristics monitored for the sand filter effluents are presented in Table 6. pH of the F1 effluent varied from 7.1 to 8.6 and that of F2 varied from 7.13 to 10. The pH in F2 may be high because of the nature of the media. F2 contains one layer of brickbats, which resulted in an increase in pH. The mean turbidity was 4.4 and 4.8 NTU in run-1 for F1 and F2, respectively. As F2 contains more pore volume than F1, the turbidity of this filter effluent is quite likely to be more than that of F1. The mean turbidity in run-2 was 3.5 and 3.7 for F1 and F2, respectively. As the filter pores filled because of accumulation of solids, the filter performances were enhanced with respect to turbidity removal. Mean pH, TSS, BOD$_5$, and COD in F1 effluent was observed to be 7.81, 22 mg/L(removal 83%), 29 mg/L(removal 77%), and 83 mg/L(removal 74%), respectively, whereas, the mean pH, TSS, BOD$_5$, and CODin F2 effluent was observed to be 9.06, 26 mg/L, and 33 mg/L, respectively. Median BOD$_5$ in F2 was 27 mg/L. Reduction in the concentrations of these parameters were significant ($p<0.05$) in both the filter effluents.

Finley et al. (2007) reported total solids removal from 313–543 mg/L to 330–633 mg/L, and COD removal from 278–435 mg/L to 161–348 mg/L in treating shower and washing machine GW using PST followed by coarse filtration followed by slow sand filtration in a 8-week duration study. In another four samples 4-month study on combined GW using filtration, Al-Hamaiedeh and Bino (2010) reported mean TSS, BOD$_5$, COD, EC$_{25}$, and SAR removal from 275 mg/L, 942 mg/L, 1712 mg/L, 1830 µS/cm, and 3.3 to 128 mg/L, 108 mg/L, 489 mg/L, 1760 µS/cm, and 2.8, respectively. USEPA (2004) standard for restricted access area irrigation (areas where public access is prohibited) specifies pH 6–9, TSS≤30 mg/L, and BOD$_5$≤30 mg/L.

The standards for construction (soil compaction, dust control, washing aggregate, making concrete) are same as that of restricted access area irrigation, without any restriction on pH. The author claimed that the treated GW satisfied the Jordanian standard for irrigation of fodder crops and tree crops, but this treated effluent did not satisfy the stringent reuse standards of the USEPA (2004).

In India, CPCB (1993) standards for effluent discharge into land for irrigation prescribes pH 5.5–9.0, TSS<200 mg/L, O&G<10 mg/L, BOD$_5$<100 mg/L, and As<0.2 mg/L. Another standard, in India, for irrigation and industrial cooling prescribes EC$_{25}$<2250 µS/cm, SAR<26, and Boron<2 mg/L (CPCB, 2008). However, in the present study, both the filter effluents satisfied the USEPA (2004) and CPCB (1993; 2008) limits (Table 6). Greywater characteristics after treatment by alum, PAC, and FeCl$_3$ are presented in Table 6. The mean OD was observed to be 351±78, 190±37, and 107±28, in alum, PAC, and FeCl$_3$,respectively (Fig. 4). Drop in pH was observed after dosing each coagulant examined (Fig. 5).

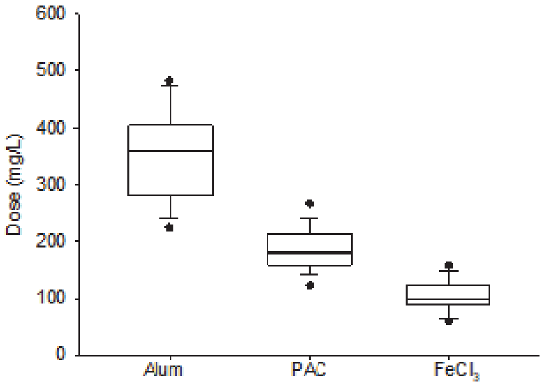


Fig. 4. Variation of optimum coagulant dose

3.4. Physicochemical treatment of greywater

Addition of alum into GW liberates carbon dioxide (CO_2) gas. This CO_2 gas then reacts with GW producing carbonic acid (H_2CO_3). Therefore, the pH of alum-coagulated water drops. In case of PAC, pH drops because of release of H^+ ions in the hydrolysis reaction.

Table 6. Characteristics (Avg±SD) of treated GW in each treatment option

Parameter	***Option 1***	***Option 2***	***Option 3***	***Option 4***	***Option 5***
pH	7.81±0.42	9.06±0.96	6.01±0.59	6.29±0.36	5.96±0.4
Turbidity (NTU)	4.35±1.91	4.74±2.04	2.01±1.31	0.99±1.57	0.91±0.68
EC$_{25}$ (µS/cm)	531±119	532±105	500± 00	499±102	518±91
TDS (mg/L)	324±72	323±72	295± 55	295±52	295±50
TSS (mg/L)	22±19	26±17	19±9	11±2	14±5
O&G (mg/L)	8±4	9.3±5	9.5±6	6.5±3	8.4±4
BOD$_5$ (mg/L)	29±15	33±18	24±11	15±12	17±8
COD (mg/L)	83±51	87±51	62±22	41± 6	39±15
NH$_3$-N (mg/L)	0.46±0.56	0.89±0.62	1.14±0.64	0.81±0.56	1.19±0.61
Chlorides(mg/L)	37±10	41±17	41±27	43±21	52±26
PO$_4$-P (mg/L)	0.18±0.12	0.18±0.11	0.08±0.08	0.04±0.04	0.05±0.05
Sulphates (mg/L)	2 ±1.67	2.1±1.55	40.1±41.76	0.8±0.65	2.5±1.51
NO$_3$-N (mg/L)	0.88±0.44	0.91±0.48	1.11±0.64	0.99±0.58	1.07±0.61
SAR	2.67±1.62	1.81±0.75	1.48±0.25	1.44±0.32	1.38±0.35
Boron (mg/L)	0.11±0.05	0.12±0.05	0.08±0.04	0.08±0.04	0.08±0.05
Arsenic (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01

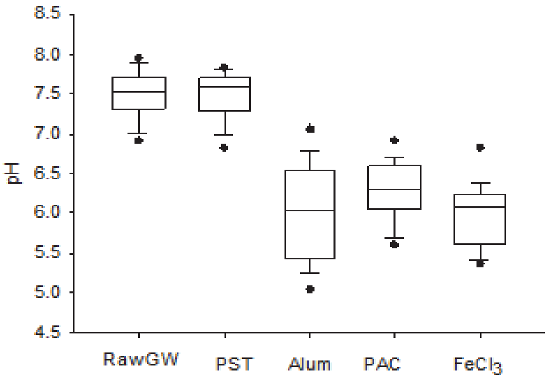


Fig. 5. Variation of pH before and after coagulation (at optimum dosage)

A typical hydrolysis reaction of PAC ($Al_2(OH)_3Cl_3$) is expressed as (Eq. 7).

$$Al_2(OH)_3Cl_3 \rightarrow Al_2(OH)_3^{+-} + 3Cl^- + 3H_2O \rightarrow 2Al(OH)_3 + 3H^+ + 3Cl^- \quad (7)$$

When an aluminium-based coagulant such as PAC is added to water, the metal ion is hydrolyzed to form aluminium hydroxide floc as well as hydrogen ions. The H^+ ions react with the alkalinity of the water and in the process, decrease the pH of the water. Hence, the pH of PAC-coagulated water drops (Gebbie, 2006).Ferric ions act as "Bronsted acids" donating a proton to the solution, which depress the pH (Antonopoulou et al., 2013). In addition, when $FeCl_3$is added to water, CO_2 gas is liberated. This CO_2 then reacts with water producing H_2CO_3. Hence, the pH of $FeCl_3$-coagulated water dropped.

In alum treatment, mean turbidity level in treated GW dropped from 94.6 NTU to 2.01 NTU (removal 98%). Pidou et al. (2008) reported turbidity removal from 46.6 to 4.28 NTU (removal 91%) in investigating shower GW using alum (dose 24 mg-Al/L). In the present study, a higher turbidity removal was obtained at an even smaller dose (17 mg-Al/L).

In the present study, a mean TSS concentration of 131 mg/L was reduced to 19 mg/L (removal 85%), mean BOD_5 concentration of 127 mg/L was reduced to 24 mg/L (removal 85%), and mean COD concentration of 314 mg/L was reduced to 62 mg/L (removal 80%). Antonopoulou et al. (2013) reported 88% TSS removal at 800 mg/L alum dose in the investigation of GW from shower, hand basin, and kitchen sink. Pidou et al. (2008) reported BOD_5 removal from 205 mg/L to 23 mg/L (removal 88%), and COD removal from 791 mg/L to 287 mg/L (removal 64%) in study of shower GW (at pH 4.5 and optimum alum dose 24 mg-Al/L). Antonopoulou et al. (2013) reported 80% COD removal at 800 mg/L alum dose. In the present study, compared to the literature, BOD_5 and COD removal was similar even at a comparatively lower alum dosage (17 mg-Al/L). In the present study, removal of TSS, BOD_5, and COD was better at a lower alum dose probably because of settling of GW prior to treatment.

In PAC treatment, mean turbidity of 94.6 NTU was reduced to 0.99 NTU (removal 99%). A mean TSS concentration of 131 mg/L was reduced to 11 mg/L (removal 92%), mean BOD_5 concentration of 127 mg/L was reduced to 15 mg/L (removal 88%), and mean COD concentration of 314 mg/L was reduced to 41 mg/L (removal 87%) at a mean optimum PAC dose of 29 mg-Al/L. In $FeCl_3$ treatment, mean turbidity of 94.6 NTU was reduced to 0.91 NTU (removal 99%). A mean TSS concentration of 131 mg/L was reduced to 14 mg/L (removal 89%), mean BOD_5 concentration of 127 mg/L was reduced to 17 mg/L (removal 87%), and mean COD concentration of 314 mg/L was reduced to 39 mg/L (removal 88%) at mean optimum $FeCl_3$ dose of 33 mg-Fe/L.

In similar studies on LGW, Friedler (2008) reported turbidity removal from 34 to 2 NTU (removal 94%) at an optimum $FeCl_3$ dose of 40 to 50 mg/L. In another study on LGW, Friedler and Alfiya (2010) reported turbidity removal from 46 NTU to 5.7 NTU (removal 88%), BOD_5 removal from 103 to 50 mg/L (removal 51%), and COD removal from 180 to 80 mg/L (removal 56%) at a dose of 22 mg-Fe/L. In another study on LGW, Antonopoulou et al. (2013) observed COD concentration of 845±167 mg/L was removed by 59% at $FeCl_3$ dose of 60 mg/L. In the present study, compared to literature, removal of turbidity, TSS, BOD_5, and COD was better at even lower $FeCl_3$ dose (107 mg-Fe/L or 33 mg-Fe/L). There were significant differences in turbidity, TSS, BOD_5, and COD concentrations after the treatment under all the three coagulant treatments ($p<0.05$). Mean pH, TSS, and BOD_5 concentrations in all the three coagulation treatment options (see Table 6) satisfy the USEPA (2004) standards, except pH in $FeCl_3$ treatment.

Hence, the treated GW was safe for restricted access area irrigation and construction (soil compaction, dust control, washing aggregate, making concrete). Concentration of TSS, O&G, and BOD_5 were also within the CPCB (1993; 2008) limits (see Table 6). Hence, the treated GW was safe for discharge into land for irrigation and industrial cooling in India.

3.5. Chlorination of treated greywater

USEPA (2004) standard for restricted access area irrigation specifies FC≤200 MPN/100 mL, and residual chlorine ≥1 mg/L. As per WHO (2006), E. coli should be <1000 CFU/100 mL for reuse of GW in unrestricted irrigation. As referred standards prescribe minimum residual chlorine in treated effluent, the present study focused on analysis of the microbial characteristics in the chlorinated samples. Chlorine dose applied, chlorine consumed, and effect of chlorine dose on microbial characteristics are presented in Table 7. Chlorine dose applied varied from 3.9 to 4.4 mg/L. The residual chlorine after 30 min contact was more than 1 mg/L. Chlorine dose with a contact time of 30 min removed the pathogens (FC and E. coli) from treated GW. Chlorinated GW satisfied the referred reuse standards (Table 7).

4. Ranking of options using Analytic Hierarchy Process

4.1. Criteria and subcriteria

The hierarchy structure used in the present study is shown in Fig. 6. Three main criteria, that is, (1) compliance of treated GW with reuse standards (CS), (2) treatment cost (TRC), and (3) ability of treatment option to work robustly (AB) were selected in the present study. Criteria CS was further divided into subcriteria, which include the reuse parameters pH, turbidity (TUR), EC_{25}, TSS, O&G, BOD_5,NH_3-N, and SAR.Chlorides, PO_4-P, sulfates, and NO_3-N were monitored but are not included in the AHP because of nonavailability of their limits in the referred reuse standards. Boron and Arsenic concentrations were very low and almost same in all the five treatment options (see Table 6). Hence, those were not included in the AHP. TC, FC, and E.coli levels were monitored after chlorine dose and were same in treated GW in all the options; therefore, they were not included in the AHP.

4.2. Greywater reuse attributes and alternatives

Treatment cost is a theoretical estimation that includes cost of construction, chemicals, energy, and manpower on annualized basis. Treatment units were designed for a flow of 10 million liters per day, keeping in view the test conditions in the present study. Further, TRC was converted to m^3/d flow (Table 8).

Ability of treatment option to work robustly is a dimension less attribute. The qualitative judgment on AB for each option was made and represented as an absolute number referring Table 4. Options 1 and 2 were rated below average. Option 3, 4, and 5 were rated as above average, very high, and high, respectively. Therefore, attribute values were assigned as 4, 4, 6, 8, and 7 for Option 1, 2, 3, 4, and 5, respectively. Any variation in the GW quality can be easily tackled by adjusting the coagulant dose; hence, the AB rating of Option 3 to 5 is higher than that of Option 1 and 2.

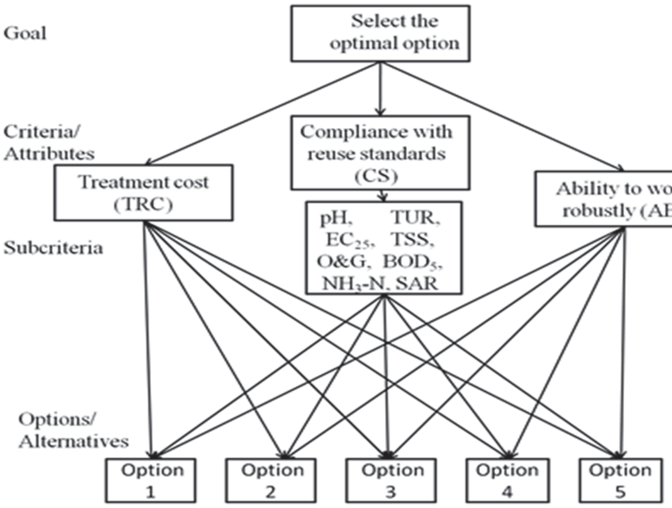


Fig. 6. Hierarchy structure of the model used in the present study

Table 7. Effect of chlorine dose on microbial characteristics (NS=3)

Parameter	*Raw GW*	*PST*	*Treated Greywater*				
			OP-1	*OP-2*	*OP-3*	*OP-4*	*OP-5*
Chlorine dose (mg/L)	0	0	4.1±0.2	4.1±0.2	4.1±0.2	4.1±0.2	4.1±0.2
Residual Chlorine (mg/L)	0	0	3.4±0.4	3.5±0.6	3.5±0.4	3.5±0.1	3.5±0.01
TC (MPN/ 100 mL)	2.6E6±1E6	2.4E6±1.4E6	<2	<2	<2	<2	<2
FC (MPN/ 100 mL)	1.7E4±4E3	1.3E4±4.7E3	0	0	0	0	0
E.coli (cfu/100 mL)	7.5E2±6E2	6.7E2±5E2	0	0	0	0	0

Table 8. Attributes and alternatives used in decision making

Alternative	*TRC*	*AB*	*ΔpH*	*TUR*	*EC_{25}*	*TSS*	*O&G*	*BOD_5*	*NH_3-N*	*SAR*
	(US\$.m^{-3}.d)[e]	*(--)*	*(--)*	*(NTU)*	*(µS/cm)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(mg/L)*	*(--)*
Option 1	20.5	4	0.7	4.35	531	22	8	29	0.46	2.67
Option 2	20.4	4	1.75	4.74	532	26	9.3	33	0.89	1.81
Option 3	28.3	6	0.99	2.01	500	19	9.5	24	1.14	1.48
Option 4	26.0	8	0.71	0.99	499	11	6.5	15	0.81	1.44
Option 5	12.4	7	1.04	0.91	518	14	8.4	17	1.19	1.38

[e] *Units in the bracket*

Compliance of treated GW with reuse standards includes mean GW characteristics of the selected attributes in each treatment option. Columns 3 to 10 (Table 8) indicate the subcriteria of the criteria CS. Subcriteria pH was transformed to ΔpH as (Eq. 8):

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

pH is a reuse standard that is preferred neither minimum nor maximum. All the referred standards prescribe a range, that is, 6–9 (USEPA, 2004); 5.5–9 (CPCB, 1993). Basically, pH of water varies from 0 to 14. Water at pH 7 is neutral. Therefore, Eq. (8) measures the deviation of pH from 7 (which gives it a nonnegative value). With this transformation, the attribute pH is used as ΔpH and is now an attribute of minimization in the present study.

4.3. Normalized data

The attributes were normalized as mentioned in section 2.5. Table 9 presents the normalized matrix. Attribute AB is a beneficial attribute and is a case of maximization. Other attributes are nonbeneficial and are minimized.

4.4. Pairwise comparison matrix and priority weights

The pairwise comparisons determine the relative importance of the criteria and subcriteria, which was rated by the 9-point scale as shown in Table 4. The intensity of importance varies from 1 to 9.

Table 10 shows the pairwise comparison of the main criteria as indicated in Fig. 6.The consistency of the judgment matrix is tested by calculation of CI as per Eq. 5. In the present study, the exact values were used in comparing attributes in the relative importance matrix; therefore, CI was zero. The CR was calculated as per Eq. 6. Here, λmax=3, M=3, CI=0, RI_3=0.52 (Saaty, 1980), and CR=0. Hence, the matrix was consistent and the priority weights were valid. The pairwise comparison matrix and priority weights for subcriteria of CS are presented in Table 11. In this matrix, λmax=8, M=8, CI=0, RI_8=1.4 (Saaty, 1980), and CR=0. Therefore, this matrix was also consistent.

4.5. Global priority weights (GPW)

As there are no subcriteria in TRC and AB, their GPWs are same as priority weights calculated in Table 10. Criteria CS has subcriteria and needs conversion of weights obtained in Table 11 by multiplying their criteria weight (i.e. 0.4091) (Table 12).

4.6. Selection Index

Selection Index is obtained by multiplying normalized data in Table 9 by GPW. For example, SI for Option 1= 0.605x0.2727 +0.5x0.3182 +1x0.0636 +0.209x0.0455 +0.940x0.0364 +0.5x0.0545 +0.813 x0.0545 +0.517 x0.0636 +1 x0.0455 +0.517 x0.0455=0.605. Here, option 5 has the highest SI (Table 13).

Table 9. Normalized data of the attributes

Alternative	*TRC*	*AB*	*ΔpH*	*TUR*	*EC$_{25}$*	*TSS*	*O&G*	*BOD$_5$*	*NH$_3$-N*	*SAR*
Option 1	0.605	0.5	1	0.209	0.940	0.500	0.813	0.517	1	0.517
Option 2	0.608	0.5	0.4	0.192	0.938	0.423	0.699	0.455	0.517	0.762
Option 3	0.438	0.75	0.707	0.453	0.998	0.579	0.684	0.625	0.404	0.932
Option 4	0.477	1	0.986	0.9192	1	1	1	1	0.568	0.958
Option 5	1	0.875	0.673	1	0.963	0.786	0.774	0.882	0.387	1

Table 10. Pairwise comparison matrix and priority weights for main criteria

Criteria/ Attribute	*Mat A1*			*Geometric mean*	*Mat A2*	*Mat A3*	*Mat A4*
	TRC	*AB*	*CS*		*Priority weights*	*=Mat A1 x Mat A2*	*=Mat A3/Mat A2*
TRC	1	0.857	0.667	0.830	0.2727	0.818	3
AB	1.167	1	0.778	0.968	0.3182	0.955	3
CS	1.500	1.286	1	1.245	0.4091	1.227	3

Table 11. Pairwise comparison matrix and priority weights for subcriteria of CS

Subcriteria	*ΔpH*	*TUR*	*EC$_{25}$*	*TSS*	*O&G*	*BOD$_5$*	*NH$_3$-N*	*SAR*	*Geometric mean*	*Priority weights*
ΔpH	1	1.4	1.75	1.166	1.166	1	1.4	1.4	1.264	0.1556
TUR	0.714	1	1.25	0.833	0.833	0.714	1	1	0.903	0.1111
EC$_{25}$	0.571	0.8	1	0.666	0.666	0.571	0.8	0.8	0.722	0.0889
TSS	0.857	1.2	1.5	1	1	0.857	1.2	1.2	1.083	0.1333
O&G	0.857	1.2	1.5	1.000	1	0.857	1.2	1.2	1.083	0.1333
BOD$_5$	1.000	1.4	1.75	1.166	1.166	1	1.4	1.4	1.264	0.1556
NH$_3$-N	0.714	1	1.25	0.833	0.833	0.714	1	1	0.903	0.1111
SAR	0.714	1	1.25	0.833	0.833	0.714	1	1	0.903	0.1111

Table 12. Attributes and corresponding global priority weights

Criteria	***TRC***	***AB***	***CS***							
Subcriteria	**--**	**--**	ΔpH	***TUR***	EC_{25}	***TSS***	***O&G***	BOD_5	$NH_3\text{-}N$	***SAR***
GPW	0.2727	0.3182	0.0636	0.0455	0.0364	0.0545	0.0545	0.0636	0.0455	0.0455

Table 13. Selection index

Alternative	***Selection Index***	***Rank***
Option 1	0.605	4
Option 2	0.541	5
Option 3	0.629	3
Option 4	0.831	2
Option 5	0.879	1

This indicates that option 5 is the best management option for treating GW in the present study. Option 4 has second rank in SI; hence, it is the next optimal option. And, finally, the selection string will be Option 5-4-3-1-2. Whereas, considering only CS, the selection string will be Option 4-5-1-3-2.

5. Conclusions

Based on mean concentrations of the parameters, almost all the treatment options examined could produce GW quality suitable for reuse in restricted access area irrigation, construction, and industrial cooling.

Performance of the filters can be improved by selecting an effective sand size less than 0.3 mm and media depth of more than 60 cm. Treating GW using multiple stage filtration, treatment using aeration followed by filtration, and so on could be a further scope for research.

As per AHP, considering due importance of various attributes, the selection string was Option 5-4-3-1-2. However, comparison of different treatment options using different types of GW and their ranking by multiple criteria decision-making tools could provide further scope for research.

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