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Effect of coagulant in greywater treatment for reuse: selection of optimal coagulation condition using Analytic Hierarchy Process

Dilip M. Ghaitidak*, Kunwar D. Yadav

Department of Civil Engineering, SV National Institute of Technology (SVNIT), Surat 395007, India, Tel. +91 8511084370; email: dmghaitidak@gmail.com (D.M. Ghaitidak)

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ABSTRACT

The objective of the present study was to (i) examine the effect of the coagulants on greywater (GW) characteristics under variable pH conditions, (ii) assess the potential of treated GW for reuse, and (iii) select optimal coagulation condition (pH and optimum dose) using Analytic Hierarchy Process (AHP). The effect of coagulants (alum and lime) was studied under four different pH conditions (8.5, 7.5, 6.5 and 5.5). Multiple linear regression models were built with optimum coagulant dose (OD) vs. pH, turbidity removal and alkalinity consumed. R^2 values ranged from 0.771 to 0.852 in case of alum and from 0.778 to 0.949 in lime treatment. In alum treatment, turbidity removal was above 88%, biochemical oxygen demand removal was in the range 53–77%, and *Escherichia coli* removal was 95–99% under the pH conditions examined. It was observed that alum-treated GW satisfied most of the reuse standards for the discharge of effluents into land for irrigation and industrial cooling in India. Total eight alternatives were ranked using AHP, considering nine criteria/sub-criteria. Using AHP, the optimal alternative selected was alum treatment at pH 5.5 with OD 204 mg/L and the worst was lime treatment at pH 8.5.

Keywords: Greywater reuse; Coagulant; Jar test; Analytic Hierarchy Process; Ranking

1. Introduction

Greywater (GW) is a wastewater from kitchen, bath and laundry, excluding wastewater from toilets. GW from bathroom, showers, tubs and clothes washing machines sources is termed as light greywater (LGW) [1,2]. In order to reduce the gap between water availability and water demand, there is a need of wastewater reuse after proper treatment. In a household, the proportion of GW flow is around 50–80% of the total wastewater flow [3]. Hence, GW reuse can be an effective measure for saving water on the domestic level and reducing load on wastewater treatment plant. GW is not suitable for direct use, but can be useful for non-potable reuse such as irrigation, toilet flushing and ground water recharge [2,4].

The finely dispersed particles (colloids) in the wastewater bear negative electric charges which repel them from each other. Therefore, they remain in a stable equilibrium which ultimately retards their settling process. Coagulants, usually bears a positive charge and can neutralize the negative charge on the colloids. Thus, coagulation/flocculation process involves charge neutralisation, and floc formation leading to rapid settling of the colloidal and suspended impurities.

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*Corresponding author.

Though the alum and lime have been used in domestic wastewater treatment, the investigations particularly on GW by using those are quite limited [5,6]. GW differs significantly from domestic wastewater in biodegradability, nutrient content, organic matter and in many more characteristics [7,8]. Therefore, the research findings on domestic wastewater may not be applicable to GW. Hence, investigation on GW using alum and lime is, yet, a point of research. Table 1 presents summary of reported research on GW treatment using alum and lime. The pH of water plays an important role in deciding the amount of coagulant required [9]. There was hardly any study on GW evaluating optimum alum dosage. No study was reported on GW evaluating optimum lime dosage under variable pH conditions. Moreover, most of the studies lack

Table 1
Summary of reported research on greywater treatment using alum and lime

Reference	Main features	Main conclusions	Remarks
Pidou et al. [7]	Tested bath, shower, hand basin greywater Bench scale study pH adjusted to chosen value (4.5, 6 and 7) after dosing the alum Treatment using coagulation and magnetic ion exchange resin	Useful for treatment of low organic strength GW Useful for less stringent standards for reuse	Could not satisfy referred reuse standards
Skudi et al. [12]	Tested bath, kitchen, laundry greywater Bench scale study Treatment comprised alum coagulation followed by sand filtration Filtrate pH was adjusted between 6.5 and 8.5	Concentrations of Fe, Mn, Ca, Mg, Pb and Hg complied with the set standards for potable water of the country	Alum dose was not optimised Economic evaluation was not reported Effect of coagulation was not separated Alum dose used was very high
Kariuki et al. [13]	Tested kitchen, laundry, hand basin greywater Pilot scale study Treatment using alum coagulation followed by disinfection	GW treatment system could produce effluent complying with pathogen limit in the referred standards	Alum dose was not optimised Economic evaluation was not reported Important reuse parameters like BOD_5, TSS were not monitored
Kar and Gupta [14]	Tested bath, laundry, kitchen, greywater Bench scale study Treatment using lime and alum coagulation followed by filtration and disinfection	The study concluded that the cost of the system may be recovered in two years	Lime/alum doses given were not reported Method of coagulation not reported No reference to any specific reuse standards
Antonopoulou et al. [15]	Tested shower, hand basin, kitchen greywater Bench scale study Treatment using alum coagulation followed by sand filtration	Alum resulted higher TSS and COD removal compared to ferric chloride	Alum dose was not optimised Cost aspect was not reported No reference to any specific reuse standards

Note: BOD_5, five day biochemical oxygen demand; TSS, total suspended solids; COD, chemical oxygen demand.

of monitoring of a complete set of reuse parameters for a particular reuse according to national or international standards.

Analytic Hierarchy Process (AHP) is a well-known multi-criteria decision-making method that has been widely applied to solve problems in many fields [10]. At present, applications of multi-attribute decision-making to GW investigations are quite limited. Chen et al. [11] 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 use AHP in selecting the optimal coagulation condition (pH and optimum dose) using AHP.

In view of the above, the objective of the present study was to (i) examine the effect of the coagulants on GW characteristics under variable pH conditions, (ii) assess the potential of treated GW for reuse, and (iii) select optimal coagulation condition (pH and optimum dose) using AHP. The effects of two coagulants (alum, and lime) were studied under four different pH conditions (pH 8.5, 7.5, 6.5 and 5.5). GW parameters were monitored at optimum coagulant dosages for targeting reuse in restricted access area irrigation, construction, and industrial cooling. The results were analysed using descriptive and multivariate statistics.

2. Materials and methods

2.1. Greywater

Real GW was used in the study. GW was collected from a students' hostel of capacity 400 located at Sardar Vallabhbhai National Institute of Technology (SVNIT), Surat, India. The sources of GW were handbasins, showers and bathrooms. GW was collected in a collection tank (CT). Samples were collected at 10 am in the morning. Around 60-L of GW was taken from CT for the experimental purpose and the remaining GW was discarded. The CT was washed each time before use with clean potable water to avoid any carry-over of contaminants. The experiments were started immediately after the collection of GW. The study was carried out for six months during December 2012–June 2013.

2.2. Experiments

Alum ($Al_2(SO_4)_3 \cdot 18H_2O$), and lime ($Ca(OH)_2$) were used in the study. A six-paddle stirrer jar test apparatus (with rotating blades) was used in GW coagulation/flocculation. Six jars, capacity 1 L each, were used in each jar test. H_2SO_4 (1 N) or NaOH (1 N) was used to adjust the pH of raw GW. For each sample four jar tests were conducted by adjusting pH to 8.5, 7.5, 6.5 and 5.5 and optimum doses were obtained. The pH adjusted raw GW was then subjected to jar test using a coagulant (alum or lime). A rapid mixing at 120 rpm for 90 s and a slow mixing at 30 rpm for 15 min were adopted. Flocculated GW was settled for next 45 min. The coagulant dose corresponding to the least turbidity was considered as optimum coagulant dose (OD). Next, the supernatants from the jar corresponding to the optimum doses were analysed. The treated samples, corresponding to initial adjusted raw GW of pH equal to 8.5, 7.5, 6.5 and 5.5 were referred as A8.5, A7.5, A6.5 and A5.5, respectively, in case of alum. Similarly, those were referred as L8.5, L7.5, L6.5 and L5.5, respectively, in case of lime. All the parameters were analysed as per standard methods [16]. Reagent/laboratory grade chemicals were used in the study.

2.3. Reuse standards referred

The GW treatment was aimed to reuse the treated GW for non-potable purpose. The target reuse was irrigation, construction and industrial cooling. Therefore, the reuse standards related to the target reuse were referred. The reuse standards referred in the present study are presented in Table 2.

2.4. Statistical analysis

The results were analysed 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 was used in the present study because: (1) parameters before and after the treatments were compared, and they were of the same size, (2) parameters compared were a continuous variable. The null (H_0) and alternate hypothesis (H_1) framed in *t*-test were as Eqs. (1) and (2).

$$H_0 : \mu_R - \mu_T = 0 \tag{1}$$

$$H_1 : \mu_R - \mu_T \neq 0 \tag{2}$$

where μ_R and μ_T are mean concentrations of parameters in raw and treated GW, respectively.

The level of test confidence was 95%. The p-value < 0.05 is evidence to reject H_0, which means, the mean concentration of parameters differs significantly after treatment (i.e. $\mu_R \neq \mu_T$). Whereas, p-value > 0.05 indicates failure to reject H_0, which means mean

Table 2
Wastewater/greywater reuse standards referred in the present study

Reference	Type of reuse	Reuse standards
CPCB [17]	Discharge into land for irrigation	pH 5.5–9.0, TSS < 200 mg/L, BOD_5 < 100 mg/L, oil & grease (O&G) < 10 mg/L, arsenic < 0.2 mg/L
USEPA [18]	Restricted access area irrigation—areas where public access is prohibited	pH 6–9, TSS ≤ 30 mg/L, BOD_5 ≤ 30 mg/L, Faecal coliforms (FC) ≤ 200 MPN/100 mL, chlorine = 1 mg/L residual (minimum)
	Construction—soil compaction, dust control, washing aggregate, making concrete	TSS ≤ 30 mg/L, BOD_5 ≤ 30 mg/L, FC<200 MPN/100 mL, Cl_2 = 1 mg/L residual (minimum)
WHO [1]	Unrestricted irrigation of crops	*Escherichia coli* (EC) < 1,000 cfu/100 mL (relaxed to 10,000 for high growing leaf crops or drip irrigation)
CPCB [19]	Irrigation and industrial cooling	Electrical conductivity (EC_{25}) < 2,250 μS/cm, sodium adsorption ratio (SAR) < 26, boron < 2 mg/L

concentration of parameters does not differ significantly after treatment (i.e. $\mu_R = \mu_T$).

Multiple linear regression models were built with OD vs. pH, turbidity removal and alkalinity consumed.

2.5. Analytic Hierarchy Process

AHP is designed to reflect the way people actually think. It can handle qualitative as well as quantitative values. The qualitative values are converted to absolute number using an appropriate scale of conversion. The dimensions of different attributes are usually different. We cannot compare attributes with different dimensions. Therefore, attributes are made dimensionless by the process of normalisation [20]. The quantitative data is normalised as mentioned in Section 4.3. The weights of the attributes (criteria) are determined by forming a pairwise comparison matrix of relative importance (see Sections 4.4 and 4.5). Alternatives are ranked using weights of the attributes and normalised data (see Section 4.6).

The geometric mean method of AHP was used in the present study. This method is widely used due to its simplicity, easy way of determining maximum eigenvalue and reduction in inconsistency in the

Table 3
The comparison scale used in AHP and corresponding linguistic variables used

Comparison scale in AHP [21, 22] Intensity of importance	Definition	Explanation	Linguistic variables
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 favour one activity over another	Low
4	II Between 3 and 5	–	Below average
5	Strong importance	Judgment strongly favour one activity over another	Average
6	II Between 5 and 7	–	Above average
7	Very strong importance	An activity is strongly favoured and its dominance is demonstrated in practice	High
8	II Between 7 and 9	–	Very high
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation	Extremely high

Note: 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*.

judgments [20,21]. An expert opinion survey was conducted for deciding the intensity of the importance of the attributes. Table 3 presents the comparison scale used in AHP and corresponding linguistic variables used in surveying. The linguistic variables were converted to the absolute numbers. The average of the responses of all the experts was considered in forming the relative importance matrix.

3. Results and discussion

The raw GW characteristics analysed in the present study are presented in Table 4. Concentrations of the parameters monitored were within the range of literature cited. Arsenic, one of the priority pollutants, was included in the study. Only Arsenic was included in the study due to availability of prescribed reuse standards for it (see Table 2). In the present study, BOD$_5$ of raw GW ranged from 40 to 240 mg/L and COD ranged from 126 to 460 mg/L. Similarly, COD/BOD$_5$ ratio varied from 1.71 to 3.15 (2.2 ± 0.38). In the literature cited, COD/BOD$_5$ ratio was in the range of 1.52–2.8 for a shower, 1.33–2.9 for bath, and 1.88–3.6 for washbasin GW [23,24]. It was 2.33 for combined bath, laundry and washbasin GW [25]. Wastewater with COD/BOD$_5$ ratio above two is not easily treatable by biological means. Moreover, a biological process needs a minimum BOD$_5$:N:P ratio of 100:5:1 for complete BOD$_5$ removal under aerobic conditions [8]. GW does not include urine; therefore, it is expected to be deficient in N. Similarly, most of the phosphorus originates from detergents used in washing and will only be present if the laundry GW is included. 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 [24]. Thus, the high COD/BOD$_5$ ratio and nutrient deficiency of the GW supports the case of physicochemical treatment in the present study.

3.1. Effect of coagulant dose on physical and chemical characteristics

The mean optimum alum dosage was observed as 268 ± 89, 252 ± 82, 237 ± 67 and 204 ± 75 mg/L at pH 8.5, 7.5, 6.5 and 5.5, respectively. These alum dosages, in terms of aluminium were 12.8 ± 4.2, 12 ± 3.9, 11.3 ± 3.2,

Table 4
Raw Greywater characteristics

		Present study			Literature data	
Parameters	Unit	*n*	Range	Avg. ± SD	Israel [23,26]	Canada [27]
GW sources			B, S, W	B, S, W	B, S, W	S, Wm
pH	–	26	7.15–8.34	7.82 ± 0.34	7−7.43	6.7–7.6
Turbidity	NTU	26	32–145	80.3 ± 28.2		
Temperature	˚C	26	23.1–30.8	27 ± 2.3		
EC$_{25}$	µS/cm	26	536–978	648 ± 124	1,130	
Total solids (TS)	mg/L	20	464–805	610 ± 99	777−1,090	313–543
Total dissolved solids (TDS)	mg/L	20	308–620	401 ± 71		
Total suspended solids (TSS)	mg/L	20	121–322	209 ± 60	78–303	
Oil and grease	mg/L	13	22–106	77.7 ± 22	7.2−164	
Alkalinity	mg/L	23	180–420	289 ± 52		
Ammonia nitrogen (NH_3–N)	mg/L	12	0.8–5.6	2.4 ± 1.4	0.39−1.2	1.2–6.2
Phosphates (PO_4–P)	mg/L	8	0.28–1.12	0.64 ± 0.31	4.56–15	
BOD$_5$	mg/L	21	40–240	153 ± 58	44–424	
Chemical oxygen demand	mg/L	21	126–460	321 ± 94	230–645	278–435
Total coliforms (TC)	MPN/100 mL	13	5E4–9E6	1.9E6 ± 2.7E6		
Faecal coliforms	MPN/100 mL	13	1.4E3–1.7E5	5.8E4 ± 6.7E4	3.5E3–4E6	4.7E4–8.3E5
Escherichia coli	cfu/100 mL	13	205–8,183	2,558 ± 2,498		
Calcium (Ca)	mg/L	8	1.92–46.87	16.46 ± 16.19		30–44
Magnesium (Mg)	mg/L	8	14.78–30.22	22.19 ± 5.43		8–9.9
Sodium (Na)	mg/L	8	63.95–117.32	84.96 ± 17.79	112−151	20–27
SAR	–	8	2.5–3.5	2.88 ± 0.43		3.9–6.1
Boron	mg/L	8	0.06–0.31	0.14 ± 0.08	0.35−0.44	
Arsenic (As)	mg/L	8	<0.01	<0.01		

Note: *n*, number of samples; Avg., average; SD, standard deviation; B, bath; S, shower; W, washbasin; Wm, washing machine.

and 9.7 ± 3.6 mg-Al/L, respectively. In similar studies on LGW, Pidou et al. [7] observed an optimum alum dose of 32, 28 and 24 mg-Al/L for pH values of 7, 6 and 4.5, respectively. Fig. 1 shows the effect of pH on optimum coagulant dosage. In the present study, OD was also reduced as per decrease in pH. The average optimum lime dosage was observed as 249 ± 100, 254 ± 114, 222 ± 130 and 218 ± 126 mg/L for GW at pH 8.5, 7.5, 6.5 and 5.5, respectively.

The effect of coagulant dose on pH is shown in Fig. 2. It was observed that, pH of alum-treated GW was dropped as alum dose increased. When alum is added in water, carbon dioxide gas is liberated. This CO_2 then reacts with water producing carbonic acid (H_2CO_3). Hence, the pH of alum-coagulated GW drops. Lime, when added to water, increases alkalinity which results in an increase in ions (some of which are positively charged). The positively charged ions attract the colloidal particles leading to floc formation [28]. During alum treatment, mean residual turbidity was decreased with a decrease in pH; whereas, in lime treatment residual turbidity decreased with increase in pH.

In alum-treated GW, mean pH (except A5.5) levels satisfied the USEPA [18] standards for restricted access area irrigation and CPCB [17] standards for discharge into land for irrigation. Whereas, in lime treatment; pH of L5.5 satisfied both the above reuse standards.

The effect of coagulant dose on turbidity is shown in Fig. 3. In alum treatment, mean turbidity level of 74.8 NTU was reduced to 8.7 (removal 88%), 8.4 (removal 89%), 8.1 (removal 89%), 5.8 NTU (removal 92%) at pH 8.5, 7.5, 6.5 and 5.5, respectively. Pidou et al. [7] reported turbidity removal from 46.6 to 4.28 NTU (removal 91%) in investigating shower GW using alum (at pH 4.5 and alum dose 24 mg-Al/L). In the present study, a similar turbidity removal was obtained at an even smaller dose (9.7–12.75 mg-Al/L), probably due to GW characteristics.

In the present study, a good correlation of the coagulant dose was observed with GW pH, turbidity

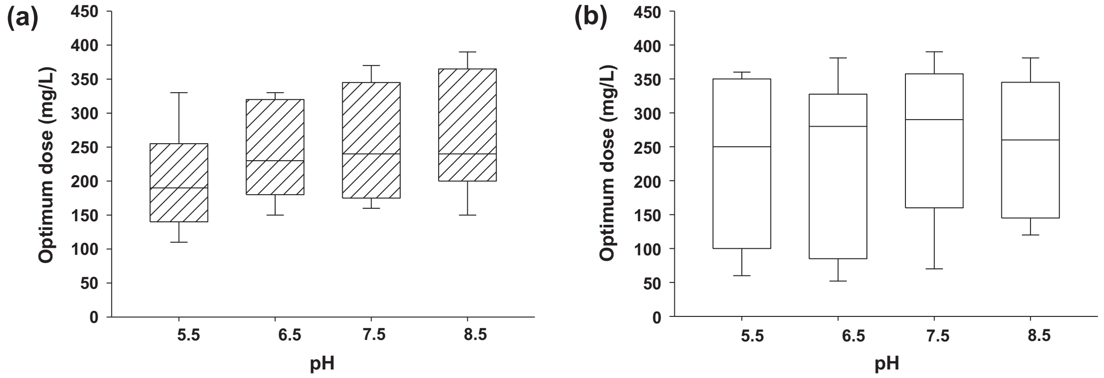

Fig. 1. Effect of pH on OD (a) alum, (b) lime.

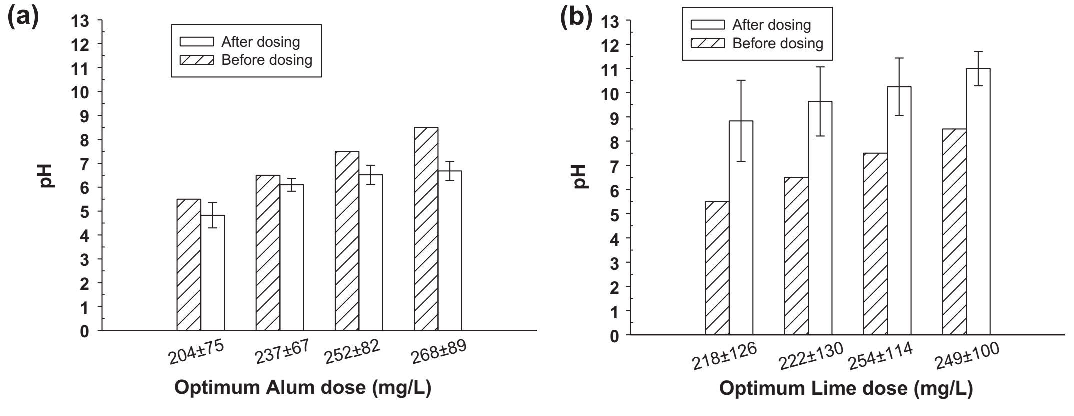

Fig. 2. Effect of coagulant dose on pH (a) alum, (b) lime.

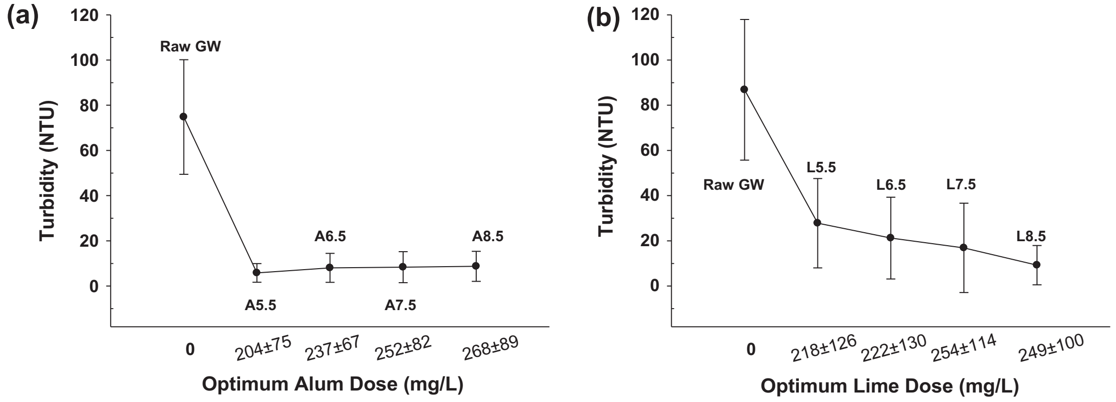

Fig. 3. Effect of coagulant dose on turbidity (a) alum, (b) lime.

removal and alkalinity consumed. Hence, these parameters were considered in developing a multiple regression model. Table 5 indicates coefficients (Y_0, c_1, c_2 and c_3) obtained in regression analysis corresponding to Eq. (3) in different coagulation conditions examined.

$$Y = Y_0 + c_1 \times X_1 + c_2 \times X_2 + c_3 \times X_3 \tag{3}$$

where Y = optimum coagulant dose (as mg-Al/L for alum; or mg/L for lime); Y_0 = constant; X_1 = pH of treated GW; X_2 = turbidity removal (%); X_3 = alkalinity consumed (%). The above equation can be helpful for taking initial trial in the jar test (i.e. adding coagulant dose) by targeting percent turbidity removal and alkalinity consumption for a particular raw GW pH. The above equation was applicable in temperature range from 23 to 31°C. This model was not applicable at pH 5.5 and 8.5 in lime treatment.

The "Multiple R" is the multiple correlation coefficient(varies from −1 to +1) and it measures the strength of association among the variables in the model. $R = -1$ indicates perfect negative correlation, $R = +1$ is perfect positive correlation, and $R = 0$ indicates no correlation. In the present study, R varied from 0.878 to 0.923 in case of alum; and, from 0.882 to 0.974 in the case of lime, indicating a good association among the variables in the model. The parameter R^2 is called as the coefficient of multiple determination of a regression model. R^2 takes values from 0 to 1. The value closer to 1 indicates a stronger prediction of response variable (RV) by predictors; and R^2 equal to 0 indicates no relationship between the predictor variables and RV [29]. In the present study, R^2 was above 0.771 which indicates a good efficiency of regression models built. Significance F is the p-value indicating the significance of the regression. In the present study, the level of confidence used in the regression was 95%; therefore, the p-value < 0.05 indicates that regression was significant at the 5% level of significance.

Table 5
Coefficients of the model obtained in regression analysis

Coefficients	Alum treatment				Lime treatment	
	A8.5	A7.5	A6.5	A5.5	L7.5	L6.5
Y_0	99.47	28.81	91.29	42.92	−486.07	577.71
c_1	−11.576	−5.315	−11.860	−6.920	52.84	76.761
c_2	−0.077	0.194	−0.002	0.089	2.66	0.426
c_3	−0.060	0.021	−0.120	−0.101	0.00	1.007
Multiple R	0.917	0.893	0.878	0.923	0.882	0.974
R^2	0.843	0.798	0.771	0.852	0.778	0.949
Significance F	0.0030	0.0080	0.0120	0.0027	0.0051	~0.00

Note: A8.5, A7.5, A6.5, and A5.5 indicate alum coagulation at pH 8.5, 7.5, 6.5 and 5.5, respectively. Similarly, L7.5 and L6.5 indicate lime coagulation at pH 7.5 and 6.5, respectively.

Concentration of total suspended solids (TSS) in alum-treated GW was reduced from 205 to 46 (removal 78%), 35 (removal 83%), 36 (removal 82%) and 49 mg/L (removal 76%) at pH 8.5, 7.5, 6.5 and 5.5, respectively; and TSS of lime-treated GW was reduced from 215 to 41 (removal 81%), 61 (removal 72%), 67 (removal 69%) and 68 mg/L (removal 68%) at pH 8.5, 7.5, 6.5 and L5.5, respectively. Antonopoulou et al. [15] reported 88% TSS removal at 800 mg/L alum dose (without previous pH adjustment) in the investigation of GW from shower, hand basin and kitchen sink. In the present study, TSS removal of around 82% was obtained at pH 7.5 and 6.5, at alum dose of 252 and 237 mg/L, respectively; which is nearly 30% of alum dose as reported in the referred literature. This indicates that the variation in pH and evaluating optimum dosage can reduce a coagulant demand significantly for similar removal efficiency.

In alum treatment, both charge neutralization and sweep flocculation mechanisms were effective in TSS removal at pH 7.5 and 6.5. Whereas, at pH 5.5, charge neutralization may be dominating; and at pH 8.5, due to high pH and corresponding high alum dose, sweep flocculation may be dominating [30]. A rise in pH from 4 to 6 causes eight times reduction in charge neutralising capacity of alum [31]. Therefore, at higher pH there is a little scope for solids removal through adsorption and inter particle bridging. Though the rise in pH reduces neutralising capacity and affects the TSS removal, a presence of alkalinity is required to form the aluminium hydroxide flocs. Around 0.45 mg/L alkalinity is required per 1 mg/L of alum for its complete hydrolysis into aluminium hydroxide [8]. In lime treatment, the pH of the treated samples was very high; therefore, the sweep flocculation might be the dominating mechanism for solids removal.

Median TSS concentrations in alum-treated GW were 29, 22, 23 and 22 mg/L at pH 8.5, 7.5, 6.5 and 5.5, respectively. Hence, alum treatment satisfied USEPA [18] and CPCB [17] reuse standards referred. Lime-treated GW satisfied CPCB [17] reuse standards for discharge into land for irrigation. TSS removal after treatment was significant under all the four pH conditions for both the coagulants ($p < 0.05$).

Mean BOD_5 concentration in alum-treated GW was reduced from 153 to 72 (removal 53%), 35 (removal 77%), 47 (removal 69%) and 55 mg/L (removal 64%,) and mean COD was reduced from 318 to 136 (removal 57%), 73 (removal 77%), 97 (removal 70%) and 111 mg/L (removal 65%) at pH 8.5, 7.5, 6.5 and 5.5, respectively. Pidou et al. [7] reported BOD_5 removal from 205 to 23 mg/L (removal 88%), and COD removal from 791 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. [15] reported 80% COD removal at 800 mg/L alum dose. In the present study, BOD_5 removal was slightly less and COD removal was similar to the literature cited, but at a comparatively lower alum dosage (i.e. 204–268 mg/L). In lime treatment, BOD_5 removal was 41 ± 23, 63 ± 24, 57 ± 22 and 53 ± 26%; and COD removal was 41 ± 25, 63 ± 24, 60 ± 18 and 58 ± 18% at pH 8.5, 7.5, 6.5 and 5.5, respectively. BOD_5 concentrations after each treatment varied significantly from raw GW concentrations under all the four pH conditions ($p < 0.05$). Mean BOD_5 concentrations complied reuse standards for discharge into land for irrigation in India [17] in both the coagulants tested and under all the four pH conditions.

Oil and grease (O&G) concentrations were above 10 mg/L. Pre-treatment of GW (e.g. providing oil and grease trap in GW collection stream) and coagulation/flocculation may reduce O&G concentrations to fit for reuse. An arsenic concentration in raw GW was <0.01 mg/L and boron was 0.14 ± 0.08 mg/L. Mean EC_{25} was observed between 724 and 765 μS/cm after alum treatment and that of in lime treatment was 795–835 μS/cm. Arsenic, boron and EC_{25} were satisfying CPCB [19] reuse standards for irrigation and industrial cooling.

During alum treatment, the average residual levels of the parameters TSS and BOD_5 were low at pH 7.5. Here, pre-adjusted pH 7.5 was resulted to 6.5 ± 0.4 after treatment. Sharp [31] observed optimum dose of aluminium-based salts under acidic conditions (pH 5–6) in removal of natural organic matter. Antonopoulou et al. [15] did not observe any effect of pH on removal of parameters (TSS, COD). According to the present study, pH 6.52 ± 0.4 may be an optimum pH for treating LGW using alum.

3.2. Effect of coagulant dose on microbiological characteristics

In alum treatment, mean TC count of 5.86E6 MPN/100 mL was reduced to 1.3E5 (removal > 98%), 4.4E4 (removal >99%), 3.1E3 (removal >99%) and 1.0E3 MPN/100 mL (removal >99%); mean FC count of 3.7E4 MPN/100 mL was reduced to 183, 177, 124 and 91 MPN/100 mL; and mean EC count of 2,815 cfu/100 mL was reduced to 135, 115, 94 and 29 cfu/100 mL at pH 8.5, 7.5, 6.5 and 5.5, respectively. Pidou et al. [7] reported TC removal from 56,500 to <1 and EC from 6,490 to <1 (removal >99.9%), at pH 4.5 and optimum alum dose 24 mg-Al/L. Kariuki et al. [13] observed no reduction in TC for the kitchen as well as laundry GW, using alum. In the present study, at pH 6.5 and 5.5, the percentage removal of TC and FC was observed close to that of Pidou et al. [7] even at a smaller dose of 11.26 ± 3.2 and 9.7 ± 3.5 mg-Al/L, at pH 6.5 and 5.5, respectively. The removal might be better due to an acidic condition rather than floc settling, where treated GW pH of these samples was in the range 5.58–6.47, and 4.04–5.43, respectively.

In the present study, in lime treatment, mean TC count of 3.4E6 MPN/100 mL was reduced to 1.5E4, 2.3E4, 3.0E4 and 6.6E4; mean FC count of 8.1E4 MPN/100 mL was reduced to 2,450, 3,835, 4,370 and 7,052 MPN/100 mL; and mean EC count of 2,258 cfu/100 mL was reduced to 282, 473, 723 and 921 MPN/100 mL at pH 8.5, 7.5, 6.5 and 5.5, respectively. Kar and Gupta [14] observed some coliform destruction with $Ca(OH)_2$ treatment (coliform count and dosage were not reported) of GW from bath, cloth washing and kitchen. Further treatments of ultrafiltration, ultraviolet and chlorination were required to make the lime-treated effluent bacteria free.

The paired *t*-test indicated significant differences in all the bacteriological (TC, FC and EC) counts, before and after the treatment under all the four pH conditions at 5% level of significance ($p < 0.05$) for both the coagulants tested.

FC counts in all the alum-treated samples were within USEPA [18] limits and were safe for restricted access area irrigation and construction. Though the FC count complied with reuse standards; treated GW should be chlorinated to prevent regrowth of pathogens and to maintain residual chlorine above 1 mg/L [18]. Both alum and lime treated GW satisfied WHO [1] standards for unrestricted irrigation and were safe from *Escherichia coli* point of view. However, even after treatment, the intrusion of GW to water sources should be prevented to avoid any health consequences that are likely to arise.

4. Ranking of alternatives using AHP

4.1. Criteria and sub-criteria

The hierarchy structure used in the present study is shown in Fig. 4. Three main criteria (1) coagulant cost (CC), (2) compliance of treated GW with reuse standards (CS), and (3) OD was selected in the study. Criteria CS were further divided into sub-criteria which include the reuse parameters pH, turbidity (TUR), TSS, BOD_5, O&G, FC and EC.

TS, TDS, NH_3–N, and PO_4–P were monitored but not included in AHP due to the non-availability of their limits in the referred reuse standards (see Table 2). Concentrations of boron and arsenic were very low in raw GW itself. Hence, those were not included in decision-making.

4.2. GW reuse attributes and alternatives

Attributes and alternatives used in decision-making are presented in Table 6. CC was obtained from enquiry in the nearby market. OD was the optimum coagulant dose observed in each pH condition. Columns 3–9 indicate the sub-criteria of CS. Sub-criteria pH was transformed to ΔpH as Eq. (4)

$$\Delta pH = |(7 - pH)| \tag{4}$$

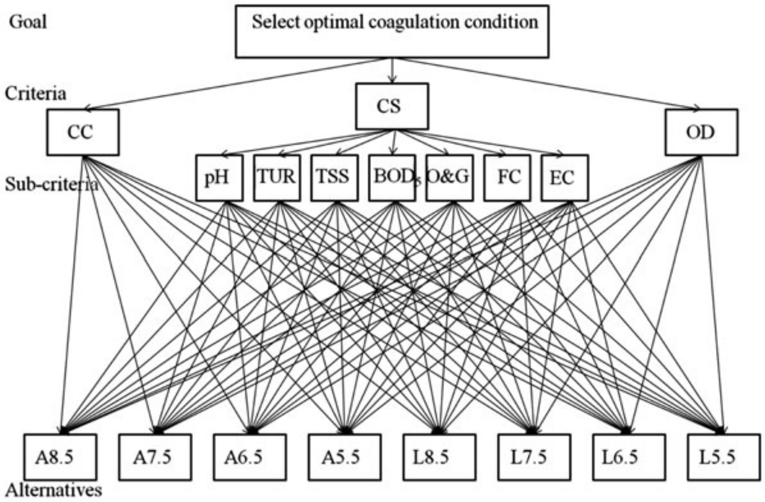

Fig. 4. Hierarchy structure of the model used in the present study.

Table 6
Attributes and alternatives used in decision-making

Alternative	CC (US$/T)	OD (mg/L)	ΔpH (−)	TUR (%)	TSS (%)	BOD_5 (%)	O&G (%)	ΔFC (log)	ΔEC (log)
A8.5	190	268	0.32	88.4	77.6	52.9	44.9	2.31	1.32
A7.5	190	252	0.48	88.8	82.9	77.1	55.1	2.32	1.39
A6.5	190	237	0.90	89.2	82.4	69.3	53.6	2.48	1.48
A5.5	190	204	2.17	92.2	76.1	64.1	52.2	2.61	1.99
L8.5	180	249	3.99	89.4	80.9	39.0	66.3	1.52	0.90
L7.5	180	254	3.24	80.5	71.6	63.6	77.7	1.33	0.68
L6.5	180	222	2.64	75.6	68.8	60.4	61.5	1.27	0.49
L5.5	180	218	1.83	68.0	68.4	57.8	56.8	1.06	0.39

Note: CC, coagulant cost; OD, optimum dose; ΔpH, deviation of pH from 7; TUR, turbidity; O&G, oil and grease; ΔFC, Faecal coliforms; ΔEC, *Escherichia coli*; %, percentage removal; Log, log removal.

pH is a reuse standard which is preferred neither minimum nor maximum. All the referred standards prescribe a range (see Table 2). Basically, pH of water varies from 0 to 14. Water at pH 7 is neutral. Therefore, Eq. (4) measures the deviation of pH from 7 (which gives is a positive value). With this transformation, the attribute pH was used as ΔpH and was an attribute of minimisation.

Percentage removal (%R) of parameters TUR, TSS, BOD_5 and O&G were calculated using Eq. (5).

$$\%\mathrm{R} = (C_R - C_T) \times 100/C_R \tag{5}$$

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

Removal of parameters, FC and EC were calculated using Eq. (6) and were represented as ΔFC and ΔEC, respectively.

$$\Delta C = \log_{10}(C_i) - \log_{10}(C_e) \tag{6}$$

where $\Delta C = \Delta\mathrm{FC}$ or $\Delta\mathrm{EC}$; C_i = FC or EC count in raw GW; C_e = FC or EC count in treated GW.

4.3. Normalised data

Table 7 presents normalised data of attributes presented in Table 6. Attributes CC, OD and ΔpH were non-beneficial and minimised. Attributes TUR, TSS, BOD_5, O&G, ΔFC and ΔEC were the removal of the parameters; hence, those were beneficial attributes and were the cases of maximisation. For instance, minimum value of CC was 180 US$/T in alternative L5.5–L8.5. This was normalised to 1; and other normalised values of CC were obtained by dividing 180 by each CC (i.e. 180/190 = 0.95). Maximum turbidity removal was 92.2% in alternative A5.5. Therefore, all the turbidity values were divided by 92.2 so that normalised turbidity value at A5.5 will be 1 and that in other alternatives will be <1 as shown in Table 7.

Table 7
Normalisation of the attributes in each alternative

Alternative	CC	OD	ΔpH	TUR	TSS	BOD_5	O&G	ΔFC	ΔEC
A8.5	0.95	0.76	1	0.96	0.94	0.69	0.58	0.89	0.66
A7.5	0.95	0.81	0.67	0.96	1	1	0.71	0.89	0.70
A6.5	0.95	0.86	0.36	0.97	0.99	0.90	0.69	0.95	0.74
A5.5	0.95	1	0.15	1	0.92	0.83	0.67	1	1
L8.5	1	0.82	0.08	0.97	0.98	0.51	0.85	0.58	0.45
L7.5	1	0.80	0.10	0.87	0.86	0.82	1	0.51	0.34
L6.5	1	0.92	0.12	0.82	0.83	0.78	0.79	0.49	0.25
L5.5	1	0.94	0.17	0.74	0.83	0.75	0.73	0.41	0.20

4.4. Pairwise comparison matrix and criteria weights

The pairwise comparisons find the relative importance of the attributes which were rated by the nine-point scale as shown in Table 3. Table 8 shows the pairwise comparison matrix (Mat A1) and weights of the main criteria. Table 9 shows the pairwise comparison matrix and local weights for sub-criteria of CS.

The consistency ratio determines the acceptance of the weights. This is one of the essential check in the AHP method which aims to eliminate the possibility of inconsistency in the criteria weights. The consistency of the judgment matrix is tested by calculation of the consistency index (CI) as Eq. (7).

$$CI = (\lambda_{\max} - M)/(M - 1) \tag{7}$$

where $\lambda_{\max}$ is the maximum eigenvalue of the matrix and could be calculated from the average of matrix A4 (see Table 8), and M is the order of the matrix (here, $\lambda_{\max} = 3$, 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 Eq. (8).

$$CR = CI\ /RI \tag{8}$$

where RI is the random index which depends upon the size of relative importance matrix. Here, for main criteria CI = 0, $RI_3 = 0.52$ [21], and CR = 0.

Saaty [21] has suggested $CR \leq 0.10$ for concluding the consistency of the pairwise matrix and validating the weights. Here, $CR < 0.10$; hence, the matrix was consistent and the weights were valid.

4.5. Global priority weight

Since, there were no sub-criteria in CC and OD, their global priority weights (GPWs) were as calculated in Table 8. Criteria CS has sub-criteria and needs conversion of weights obtained in Table 9 by multiplying their criteria weight (i.e. 0.45). Table 10 presents all the attributes and their GPWs.

4.6. Selection index

Selection index (SI) is a measure of ranking the alternatives. The higher the SI, the better is the alternative. SI was obtained by multiplying normalized data in Table 7 by GPW. Here alternative A5.5 has the highest SI (Table 11). This means, treating GW using alum at

Table 8
Pairwise comparison matrix and weights for main criteria

	Mat A1						
	CC	OD	CS	Geometric mean	Mat A2 Weights	Mat A3 =Mat A1 × Mat A2	Mat A4 =Mat A3/Mat A2
CC	1	0.833	0.556	0.774	0.250	0.750	3
OD	1.2	1	0.667	0.928	0.300	0.900	3
CS	1.8	1.5	1	1.392	0.450	1.350	3

Note: Mat, matrix.

Table 9
Pairwise comparison matrix and local weights for sub-criteria of CS

	ΔpH	TUR	TSS	BOD_5	O&G	ΔFC	ΔEC	Local weights
ΔpH	1.00	1.40	1.17	1.00	1.17	1.00	1.17	0.159
TUR	0.71	1.00	0.83	0.71	0.83	0.71	0.83	0.114
TSS	0.86	1.20	1.00	0.86	1.00	0.86	1.00	0.136
BOD_5	1.00	1.40	1.17	1.00	1.17	1.00	1.17	0.159
O&G	0.86	1.20	1.00	0.86	1.00	0.86	1.00	0.136
ΔFC	1.00	1.40	1.17	1.00	1.17	1.00	1.17	0.159
ΔEC	0.86	1.20	1.00	0.86	1.00	0.86	1.00	0.136

Note: $\lambda_{\max} = 7$, M = 7, CI = 0, $RI_7 = 1.35$ [21], CR = 0.

Table 10
Attributes and corresponding GPWs

Criteria	CC	OD	CS						
Sub-criteria	–	–	ΔpH	TUR	TSS	BOD_5	O&G	ΔFC	ΔEC
GPW	0.250	0.300	0.072	0.051	0.061	0.072	0.061	0.072	0.061

Table 11
Selection index

Alternative	A8.5	A7.5	A6.5	A5.5	L8.5	L7.5	L6.5	L5.5
Selection index	0.832	0.86	0.851	0.889	0.769	0.774	0.782	0.771
Rank	4	2	3	1	8	6	5	7

pH 5.5 with optimum dose 204 mg/L was the best alternative among all the alternatives examined. Alternative A7.5 has 2nd rank in SI; hence, it will be the next optimal option. Finally the selection string will be alternative A5.5-A7.5-A6.5-A8.5-L6.5-L7.5-L5.5-L8.5. Whereas, considering only compliance to reuse standards the selection string was alternative A7.5-A8.5-A6.5-A5.5-L7.5-L8.5-L6.5-L5.5.

5. Conclusions

The pH of treated GW decreased with increase in alum dose; and the optimum alum dose decreased with a decrease in GW pH. Whereas, the GW pH had a little influence on an optimum lime dosage under the pH conditions tested. The study revealed that alum treated GW satisfied all the reuse standards (except O&G) for the discharge of effluents into land for irrigation, and industrial cooling in India. In alum treatment, removal of organic matter was observed highest at treated GW pH 6.52 ± 0.4; hence, it may be considered as optimum pH for alum treatment.

Application of AHP in ranking alternatives resulted in a selection string of alum coagulation at pH 5.5, 7.5, 6.5, and 8.5 at optimum dose of 204, 252, 237, and 268 mg/L indicating rank 1, 2, 3, and 4, respectively. Further, lime coagulation at pH 6.5, 7.5, 5.5, and 8.5 at optimum dose 222, 254, 218, and 249 mg/L indicate rank 5, 6, 7, and 8, respectively. Considering only compliance to reuse standards, the selection string of alternatives was alum coagulation at pH 7.5, 8.5, 6.5, and 5.5; and lime coagulation at pH 7.5, 8.5, 6.5, and 5.5 indicating rank 1, 2, 3, 4, 5, 6, 7, and 8, respectively. However, investigations on the effect of coagulants on different types of GW (viz. kitchen, laundry, combined GW, etc.) and ranking optimal coagulation conditions using various multi-criteria decision-making tools will be a further scope for research.

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References

[1] WHO, WHO Guidelines for the Safe use of Wastewater, Excreta and Greywater, Excreta and Greywater use in Agriculture, vol. 4, World Health Organization, Geneva, 2006.

[2] A. Gross, D. Kaplan, K. Baker, Removal of chemical and microbiological contaminants from domestic greywater using a recycled vertical flow bioreactor (RVFB), Ecol. Eng. 31 (2007) 107–114.

[3] A. Jamrah, A. Al-Omari, L. Al-Qasem, N. Abdel Ghani, Assessment of availability and characteristics of Greywater in Amman, Water Int. 31(2) (2006) 210–220.

[4] P.D. Jenssen, Design and Performance of Ecological Sanitation Systems in Norway, Ecological Sanitation Research, Stockholm Environment Institute, Stockholm, 2002.

[5] L. Abu Ghunmi, G. Zeeman, M. Fayyad, J.B. van Lier, Grey water treatment systems: A Review, Crit. Rev. Environ. Sci. Technol. 41 (2011) 657–698.

[6] D.M. Ghaitidak, K.D. Yadav, Characteristics and treatment of greywater—A review, Environ. Sci. Pollut. Res. 20 (2013) 2795–2809.

[7] M. Pidou, L. Avery, T. Stephenson, P. Jeffrey, S.A. Parsons, S. Liu, F.A. Memon, B. Jefferson, Chemical solutions for greywater recycling, Chemosphere 71 (2008) 147–155.

[8] Metcalf, Eddy, Wastewater Engineering: Treatment and Reuse, McGraw-Hill Series in Civil and Environmental Engineering, 4th ed., McGraw-Hill, New Delhi, 2003.

[9] D.J. Pernitsky, J.K. Edzwald, Selection of alum and polyaluminum coagulants: Principles and applications, J. Water Supply Res. Technol.—AQUA 55(2) (2006) 121–141.

[10] A. Ishizaka, A. Labib, Review of the main developments in the analytic hierarchy process, Expert Syst. Appl. 38 (2011) 14336–14345.

[11] Z. Chen, H.H. Ngo, W.S. Guo, A. Listowski, K. O'Halloran, M. Thompson, M. Muthukaruppan, Multi-criteria analysis towards the new end use of recycled water for household laundry: A case study in Sydney, Sci. Total Environ. 438 (2012) 59–65.

[12] J.B. Skudi, R. Wanjau, J. Murungi, C.O. Onindo, Alum treated grey water for toilet flushing, mopping and laundry work, Hydrol. Curr. Res. 2 (2011) 1–4.

[13] F.W. Kariuki, K. Kotut, V.G. Nganga, The potential of a low cost technology for the greywater treatment, The Open Environ. Eng. J. 4 (2011) 32–39.

[14] R. Kar, O. Gupta, Grey water treatment and recycling for use in household applications, Int. J. Eng. Res. Technol. 1(4) (2012) 1–10.

[15] G. Antonopoulou, A. Kirkou, A.S. Stasinakis, Quantitative and qualitative greywater characterization in Greek households and investigation of their treatment using physicochemical methods, Sci. Total Environ. 454–455 (2013) 426–432.

[16] APHA, Standard Methods for the Examination of Water and Wastewater, 21st ed., American Public Health Association, Washington, DC, 2005.

[17] CPCB, The Environment (Protection) Rules, 1986, Schedule VI (Amended 1993), Central Pollution Control Board, New Delhi, 1993.

[18] USEPA, Guidelines for Water Reuse, Report EPA/625/R-04/108, United States Environmental Protection Agency, Washington, DC, 2004.

[19] CPCB, Guidelines for Water Quality Management, Environmental Standards—Water Quality Criteria, Central Pollution Control Board, New Delhi, 2008.

[20] R.V. Rao, Decision Making in the Manufacturing Environment: Using Graph Theory and Fuzzy Multiple Attribute Decision Making Methods, Springer-Verlag, London, 2007.

[21] T.L. Saaty, The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation, McGraw-Hill, New York, NY, 1980.

[22] T.L. Saaty, How to make a decision: The analytic hierarchy process, Eur. J. Oper. Res. 48 (1990) 9–26.

[23] E. Friedler, Quality of individual domestic greywater streams and its implication for on-site treatment and reuse possibilities, Environ. Technol. 25 (2004) 997–1008.

[24] B. Jefferson, A. Palmer, P. Jeffrey, R. Stuetz, S. Judd, Grey water characterisation and its impact on the selection and operation of technologies for urban reuse, Water Sci. Technol. 50(2) (2004) 157–164.

[25] L. Abu Ghunmi, G. Zeeman, M. Fayyad, J.B. van Lier, Grey water biodegradability, Biodegradation 22 (2011) 163–174.

[26] M.J. Travis, A. Wiel-Shafran, N. Weisbrod, E. Adar, A. Gross, Greywater reuse for irrigation: Effect on soil properties, Sci. Total Environ. 408 (2010) 2501–2508.

[27] S. Finley, S. Barrington, D. Lyew, Reuse of domestic greywater for the irrigation of food crops, Water, Air, and Soil Pollut. 199 (2009) 235–245.

[28] Virginia's Community Colleges, Coagulation and Flocculation, http://water.me.vccs.edu/courses/env110/Lesson4_print.htm (consulted 12/3/2014).

[29] K. Black, Business Statistics: For Contemporary Decision Making, 6th ed., John Wiley, Hoboken, 2010.

[30] D. Ghernaout, B. Ghernaout, Sweep flocculation as a second form of charge neutralisation—A review, Desalin. Water Treat. 44 (2012) 15–28.

[31] E. Sharp, Natural organic matter coagulation, Dissertation, Cranfield University, http://dspace.lib.cranfield.ac.uk/handle/1826/2224 (consulted 7/7/2013).