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RESEARCH ARTICLE - CIVIL ENGINEERING

Treatment of Ablution Greywater for Recycling by Alum Coagulation and Activated Carbon Adsorption

Saleh Khalaf Alharbi[1] · Md Shafiquzzaman[1] · Husnain Haider[1] · Saleem S. AlSaleem[1] · Abdul Razzaq Ghumman[1]

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Abstract
A considerable amount of ablution greywater (AGW) is being produced at mosques for cleaning certain parts of the body before performing prayers. In this study, alum coagulation followed by batch and continuous AC adsorption tests was conducted to examine the removal efficiency of turbidity, COD, and BOD to evaluate the recycling potential of AGW. In coagulation experiments, optimal overall removals of turbidity (95.8%), COD (31.6%) and BOD (50.0%) were achieved at 20 mg/L of alum dose. Further, the overall removal efficiencies were enhanced by AC adsorption for COD up to 70.8% and BOD up to 57.2% at 20 min adsorption equilibrium time with 0.2 g/L of optimal AC dose. The adsorption data was well fitted to the pseudo-second-order kinetics model. Both the Langmuir and Freundlich isotherm models were found suitable to characterize the adsorption of COD and BOD on AC. Maximum adsorption capacities were calculated 175 mg/g for COD and 88 mg/g for BOD. Continuous experiments of the AGW treatment process resulted in residual turbidity less than 1 NTU and both the COD and BOD values less than 10 mg/L. Treated AGW was found suitable for unrestricted irrigation, toilet flushing, and firefighting. The estimated cost for a full-scale treatment process (1.02 US$/m^3) came out to be less than the existing cost of water production (1.09 US$/m^3) in Saudi Arabia. The study revealed that the combination of alum coagulation and AC adsorption is a sustainable treatment option for recycling of AGW in arid and semiarid regions.

Keywords Ablution greywater (AGW) · Recycling · Alum coagulation · AC adsorption · Adsorption models

1 Introduction

Most of the gulf countries, including the Kingdom of Saudi Arabia (KSA), are facing severe threats of limiting freshwater resources. Increasing population and rapid development almost in all the domains will lead to significantly increased water demand and lowering of groundwater table, in these regions [1]. In addition, renewable groundwater and surface water supplies are also being affected due to climate change impacts [2]. Municipalities are striving to supply safe drinking water to the public by spending extensive technical and financial resources for treating sea and saline groundwater [3]. Hence, high-quality supplied water should be effectively reused (or recycled) to implement sustainable development practices which also intend to achieve one of the primary objectives of Vision 2030 in KSA.

It is necessary to evaluate practical greywater recycling options for abating the pressure from limited available freshwater resources in arid regions. Greywater represents the major part of domestic wastewater originating form kitchen, bath and laundry, with low contents of pathogens, organic material, and nutrients [4]. Ablution water is also a kind of greywater produced in mosques when Muslims wash certain parts of their bodies (i.e., commonly known as 'Wudhu') to perform prayers. In most Middle Eastern countries, a large amount of ablution greywater (AGW) is being produced in mosques and has a potential to be recycled for non-potable applications. According to Prathapar et al. [5], a medium-sized mosque in a Middle Eastern country produces an average of 1000–1500 L/day of AGW. It is estimated that if around 100,000 mosques in KSA are producing AGW at the same rate, the total amount of AGW produced is around 15,000 m^3/day. Earlier studies found that AGW has less organic content, nutrients, and

✉ Md Shafiquzzaman
shafiq@qec.edu.sa

[1] Department of Civil Engineering, College of Engineering, Qassim University, Buraidah 52571, Saudi Arabia

pathogen in comparison with domestic greywater originated from washing, cooking, and bathing [6,7]. In recent years, some Middle Eastern countries, including KSA, initiated to recycle the treated greywater and wastewater for some restricted and unrestricted irrigation purposes. To date, lack of public and social awareness and sustainable treatment systems are some of the primary constraints for greywater recycling.

According to the previous studies, AGW is neutral in pH (6.92–7.10) with wide variation of COD (50–70 mg/L), BOD (20–40 mg/L), TSS (5–146 mg/L), turbidity (10–30 NTU), and E-coil (100–1000 CFU/100 mL) [7–9]. The quality of AGW suggests that a basic and simple treatment process could be applied to recycle for landscaping, toilet flushing, car washing, irrigation, etc. [6]. In the recent past, several studies evaluated the feasibility of different treatment technologies for treating and recycling greywater produced from the domestic buildings [10,11], using physical [12], chemical [13,14], biological [15–17], and integrated/hybrid [18–20] methods.

The coagulation–flocculation process using alum is a widely used chemical process for removal of suspended and colloidal particles from wastewater and greywater [14,21,22]. Although alum coagulation is highly efficient in removing TSS and turbidity from greywater, its effectiveness has been found low for the removal of organic matters such as COD and BOD [22]. Activated carbon (AC) has been widely applied to remove organic materials, odor, and taste from greywater [23–25]. Adsorption on the AC subsequent to coagulation step can enhance the removal of COD and BOD from AGW.

To our knowledge, very few researches investigated AGW treatment and most of those studies were based on physical–chemical methods using sand filtration [5,7,9,26]. Such treatment systems contain some drawbacks. Firstly, they are difficult to operate and maintain, i.e., clogging and backwashing mechanisms, for point-of-use recycling applications. Secondly, the efficiency for the removal of the organics (COD and BOD) was found to be low and the treated effluent could not meet the desired quality standards for most of the recycling applications [5,7,9,26]. Despite some disadvantages of alum coagulation and activated carbon adsorption processes, such as difficulty of regeneration of AC and spent media disposal, these processes have been widely used for wastewater treatment because of their efficacy to remove wide range of pollutants [14,21–25]. A combination of alum coagulation and AC adsorption may be an effective treatment option for AGW. Biodegradability, nutrient content, organic matter, microbiological properties, and many more characteristics of AGW significantly differ from domestic greywater [7–9]. Although alum coagulation and AC have been applied for the treatment of domestic greywater, their efficacy for treating AGW has not been evaluated, so far; hence, the findings of reported research on domestic greywater may not be applicable to AGW.

From this perspective, present study investigates the combination of alum coagulation and AC adsorption for the treatment of AGW. The primary objectives are: (1) examine the effect of alum coagulation on AGW treatment and select the optimal coagulant dose, (2) conduct batch adsorption experiments to find out optimal doses of activated carbon and perform kinetics and isotherm adsorption modeling, (3) conduct laboratory-scale continuous experiments with alum coagulation followed by AC adsorption column to optimize the operating conditions for targeting reuse applications, such as toilet flushing, landscaping, and firefighting, and (4) evaluate the economic feasibility of the full-scale unit for AGW treatment.

2 Materials and Methods

2.1 AGW Sampling

Raw AGW samples were collected from a medium-sized mosque named "Al-Ajaji Mosque" located in Buraydah City, Al-Qassim, KSA. All the samples were collected at the outlet of AGW pipe draining to the municipal sewer. During sampling, it was ensured that AGW was not mixed with black water originating from toilet flushing. AGW was collected in a 10 L polyvinyl jar and stored at 4 °C prior to laboratory analysis.

2.2 Materials

The coagulant, powdered aluminum sulfate hydrate ($Al_2(SO_4)_3 \cdot 12H_2O$), was purchased from WETICO—Water & Environment Technologies Co., Ltd., KSA. After purchasing, a 10 mg/mL fresh solution of alum was prepared by mixing 10 g of alum powder in 1 L of distilled water and used for the experiments.

Activated carbon (AC) used in this study was obtained from a CTO-10 (Riverpure, Taiwan) carbon block cartridge filter that was purchased from the local market in the city of Buraydah, KSA. The activated carbon was extracted from the filter and used for the batch adsorption study, whereas the carbon block filter itself was used for continuous experiments. The particle density of activated carbon was 372 kg/m^3, moisture content was 6.7%, and particle size ranged between 0.2 and 1.8 mm.

2.3 Laboratory Experiments

2.3.1 Coagulation Experiments with Alum

Coagulation experiments were performed to determine the removal efficiency and optimum alum doses for AGW treatment. The experiments were carried out using a standard jar test apparatus at room temperature (25 °C) and pH varied between 7.0 and 7.8. Different doses of alum (0, 5, 10, 20, 30, and 50 mg/L) were mixed with 1 L of AGW in a 1000 mL glass beaker. Coagulation experiments were performed by 2 min rapid mixing at 100 rpm followed by 20 min slow mixing at 40 rpm and finally 30 min settlement. Subsequently, the suspension was taken carefully and the concentrations of turbidity, COD, and BOD were determined.

2.3.2 Batch Experiments of AC Adsorption

Since this study evaluated the efficacy of AGW treatment by a combination of alum coagulation and AC adsorption, all the AC adsorption experiments were conducted on the AGW treated with alum, i.e., suspension of the alum coagulation. The removal of COD and BOD from the alum-treated AGW was assessed through investigating the effect of AC dose and contact time in batch adsorption experiments. All adsorption experiments were conducted at pH ranging from 7.0 to 7.8 and room temperature of 25 °C using 1000-mL capacity glass beaker and standard jar test apparatus. Effect of carbon dose was conducted using different doses of activated carbon (0.025–0.5 g/L) in 1 L of AGW sample and mixing them for 20 min at 40 rpm using standard jar test apparatus. Experiments to evaluate the effect of contact time were conducted by mixing 0.2 g/L of AC with 1 L of AGW for 0, 5, 10, 20, 30, and 60 min at 40 rpm using a jar test apparatus. The following formulas were used to estimate the removal % and amount of BOD and COD adsorption at equilibrium time (q_e).

$$\text{removal}\,\% = \frac{C_0 - C_e}{C_0} \times 100 \tag{1}$$

$$q_e\,(\text{mg/g}) = \frac{(C_0 - C_e) \times V}{m} \tag{2}$$

where C_0 and C_e denote the initial and final concentrations of BOD and COD in the solution (mg/L), m expresses the mass of the AC (g), and V is the volume of the AGW (L).

2.4 Adsorption Modeling

2.4.1 Batch Kinetic Model

Adsorption mechanism of COD and BOD on to activated carbon was examined by the pseudo-first-order (PFO) and pseudo-second-order (PSO) kinetic models.

Linear form of pseudo-first-order kinetic model is expressed as:

$$\log(q_e - q_t) = \log q_e - k_1 t \tag{3}$$

where q_t (mg/g) define the amount of adsorbed BOD and COD at time t (min) and k_1 (/min) is the pseudo-first-order rate constant. The slopes and intercepts of the liner plots of log ($q_e - q_t$) versus t were used to calculate k_1 and q_e.

Pseudo-second-order kinetic model can be expressed as:

$$\frac{1}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t \tag{4}$$

where k_2 (g/mg/min) is the pseudo-second-order rate constant. A linear plot of t/q_t versus t, gives the values of k_2 and q_e.

2.4.2 Adsorption Isotherm Models

Adsorption data were examined by both the Langmuir and Freundlich isotherm models for the adsorption of COD and BOD on to AC. A uniformly distributed monolayer sorption on to active AC surface is the basic assumption of Langmuir isotherm [27]. The linear form of Langmuir isotherm is expressed as:

$$\frac{C_e}{q_e} = \frac{C_e}{q_o} + \frac{1}{q_m k_L} \tag{5}$$

where q_o is maximum adsorption capacity (mg/g) and k_L is the Langmuir free energy adsorption constant (L/mg).

Separation factor R_L for Langmuir isotherm is expressed as:

$$R_L = \frac{1}{1 + k_L C_0} \tag{6}$$

Adsorption is unfavorable for $R_L > 1$ and $0 < R_L < 1$ for favorable adsorption. R_L value is zero for irreversible adsorption.

The basic assumption of Freundlich isotherm states that adsorption surface is heterogeneous with multilayer adsorption [28]. The linear form of Freundlich isotherm is expressed as:

$$\log q_e = \log k_f + \frac{1}{n} \log C_e \tag{7}$$

where k_f is the Freundlich constant relating to the adsorption capacity (mg/g) and $1/n$ is an empirical parameter to measure the adsorption intensity [28].

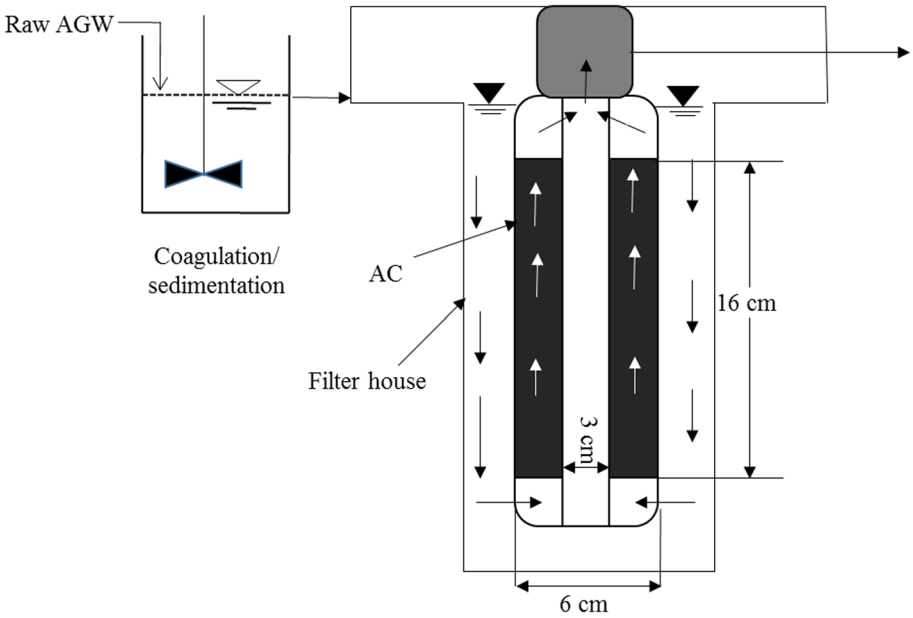

Fig. 1 Schematic diagram of continuous AGW treatment process by alum coagulation and AC adsorption

2.5 Laboratory-Scale Continuous Treatment Experiments

The schematic representation of the continuous experimental setup for AGW treatment is given in Fig. 1. The laboratory-scale AGW treatment unit consists of a coagulation/sedimentation tank followed by an AC adsorption column. As discussed earlier, CTO-10 (Riverpure, Taiwan) AC filter (available at local market) was used as adsorption column. The AC column was 16 cm in height with outer diameter of 6.0 cm and inner diameter of 3.0 cm. The active bed volume of the column was 1357 cm^3.

The adoption column was operated in up flow mode using a peristaltic pump. At the first stage, alum coagulation was performed in coagulation tank at 40 rpm and 20 min agitation time. Therefore, the hydraulic residence time (HRT) of coagulation tank is 20 min. The suspension from the coagulation tank was then fed to the AC filter at a constant flow rate of 2.25 L/h. The resulting empty bed contact time (EBCT) was set at 35 min. The treatment unit was operated continuously for 8 days. Water samples from the coagulation tank and at the effluent of AC column were collected in daily basis, and water qualities were measured.

2.6 Analytical Methods

Analyses of the water samples were performed at the laboratory of Ministry of Environment, Water, and Agriculture, Buraidah, Qassim, KSA. pH was measured using the Hach MP-6 (HACH, Loveland, CO, USA) portable pH meter. Turbidity was measured using the Hach 2100Q turbidity meter (2100Q, HACH, Loveland, CO, USA). Total dissolved solid (TDS) was measured using the Hach HQ411d TDS meter (HACH, Loveland, CO, US). Analyses for COD, BOD, PO_4-P, and NH_4-N were performed according to the Standard Methods for the Examination of Water and Wastewater Analysis prescribed by American Public Health Association (APHA) [29]. The Hach-DR5000 UV–Vis Spectrophotometer was used to measure COD (reactor digestion method), PO_4-P (acid persulfate digestion method), NH_4-N (direct ISE method) and TSS (photometric method). Five-day BOD was determined by the standard dilution method. Fecal coliform (FC) was measured using a Quanti-Tray consisting of 51 individually sealable cells.

3 Results and Discussions

3.1 Characteristics of Raw AGW

The average concentrations of primary contaminants in 10 raw AGW samples are presented in Table 1. Average pH, TSS, turbidity, COD, and BOD were measured to be 7.9, 24 (mg/L), 14.8 (NTU), 63.2 (mg/L), and 37 (mg/L), respectively. Turbidity was higher than KSA recycling standards of 5 NTU for all of the GWR applications [30]. The concentration of BOD was found to be higher than 10 mg/L which exceeds the standards for unrestricted irrigation, toilet flushing, etc. (i.e., see KSA recycling Standard A in Table 1). Average COD (63.2 mg/L) exceeded the KSA standard (50 mg/L) for all recycling applications mentioned in Table 1. Other water quality parameters such as TDS, PO_4-P, NH4-N, Fecal coliform, and total coliform are also listed in Table 1. TDS levels were found to be acceptable for all the potential recycling applications. However, Fecal coliforms (FC) levels were higher than recycling standards for unre-

Table 1 Characteristics of Raw AGW collected from the local mosque

Parameters	Raw ablution greywater (AGW)[a]			KSA reuse standard	
	Minimum	Average	Maximum	A[b]	B[c]
pH	7.7	7.9	8.1	6.0–8.4	6.0–8.4
TSS (mg/L)	19.0	24	35.0	10	40
Turbidity (NTU)	11.2	14.8	18.1	5	5
COD (mg/L)	33.0	63.2	88.0	–	50
BOD (mg/L)	19.0	37	51.0	10	40
TDS (mg/L)	192	213	245	2500	2500
PO_4-P (mg/L)	0.07	0.2	0.28	–	–
NH_4-N (mg/L)	0.27	0.34	0.44	–	–
Total coliform (MPN/100 mL)	–	1011	–	–	–
Fecal coliform (MPN/100 mL)	756	884	982	< 1	1000

[a] Values are the average of 10 Raw AGW samples
[b] A = KSA Standard for unrestricted irrigation, toilet flushing, street and firefighting [30]
[c] B = KSA Standard for restricted irrigation [30]

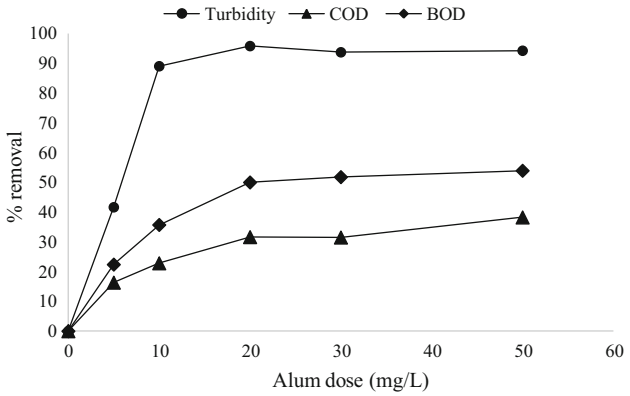

Fig. 2 % removal of turbidity, COD and BOD by jar test at different does of alum. pH = 7.0–7.8, temperature 25 °C, turbidity = 19.1 NTU, COD = 60.0 mg/L and BOD = 40.2 mg/L

stricted irrigation (Standard A). The overall water quality of raw AGW indicated the necessity of AGW treatment for potential recycling.

3.2 Alum Coagulation Experiments

Figure 2 presents the percentage removal of turbidity, COD, and BOD by alum coagulation through standard jar test experiments. Turbidity removal up to 89% was achieved at 10 mg/L alum dose and approached to the maximum removal of 94% at 20 mg/L dosage. Constant removal was observed with further increase in alum dose from 20 to 50 mg/L. Results indicated that the suspended and colloidal particles in AGW were removed by coagulation process. As presented in Fig. 2, COD and BOD removal increased with the increase in alum doses from 0 to 20 mg/L and remained steady afterward up to 50 mg/L.

This phenomenon was found consistent with the findings of a previous study showing that the COD removal efficiency increased with the increase in alum coagulant doses [31]. Previous studies reported that a high polymeric Al species is formed with increasing pH of the solution since the hydroxide species of aluminum were easily formed in the presence of high concentration of hydroxide ion [31,32]. As a result, the removal efficiency of organic was better at neutral-to-alkaline conditions. In the present study, a high polymeric aluminum hydroxide species might be formed during the coagulation experiments at pH 7.0–7.8 (see Fig. 2). These Al species are highly efficient in adsorbing organic matters resulting in reduction in both the COD and BOD form AGW. From coagulation experiments, it was observed that the optimum removals of turbidity, COD, and BOD were obtained at 20 mg/L and selected as optimum coagulant dose. Hereafter, all the batch and continuous adsorption experiments of AGW on the AC were carried out with the suspension obtained form 20 mg/L of alum dose.

3.3 Batch Adsorption Experiments

3.3.1 Effect of Carbon Dose

Percentage removals of COD and BOD from the alum-treated AGW at different doses of AC are presented in Fig. 3. The removal percentage of both the COD and BOD increased with increase in AC dose. COD removal of 70% and BOD removal of 58% were achieved at 0.2 g/L AC dose and remained steady at additional increase in AC dose to 0.5 g/L. These findings demonstrate that COD and BOD were removed from AGW by adsorption on to the active functional surface of AC used in this study. COD and BOD removals reached equilibrium at 0.2 g/L AC dose; hence, 0.2 mg/L of AC dose was selected as optimum dose.

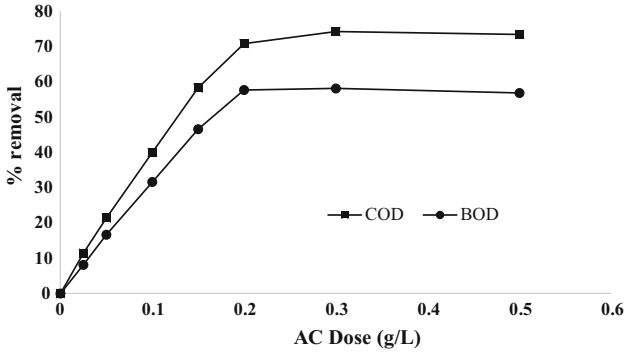

Fig. 3 % removal of COD and BOD at different does of AC. pH = 7.0–7.8, temperature 25 °C, COD = 35 mg/L and BOD = 23.4 mg/L

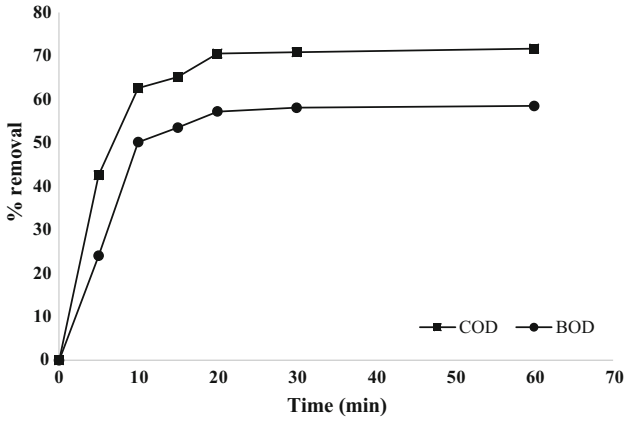

Fig. 4 % Removal of COD and BOD by AC at different mixing times. AC dose 0.2 mg/L, pH = 7.0–7.8, temperature 25 °C, COD = 35 mg/L and BOD = 23.4 mg/L

3.3.2 Effect of Contact Time

The contact time plays an important role for the removal of both the COD and BOD from AGW. Figure 4 presents the percentage removal of COD and BOD at different mixing times varying from 0 to 60 min. Rapid removal rates were observed for both the COD and BOD during first 10 min, i.e., 63% for COD and 50% for BOD. Approaching to equilibrium, 71% removal for COD and 57% for BOD were achieved at 20 min mixing and remained constant up to 60 min of the contact time. It can be observed from the nature of the removal curves in Fig. 4 that the adsorption of both the COD and BOD through activated carbon can be described in three phases. In the first phase (from 0 to 10 min), instantaneous and faster adsorption called external surface diffusion process occurred because of the availability of adequate adsorption sites on the AC [33,34]. In the second phase (10–20 min), a gradual adoption observed for both COD and BOD advocates that intra-particle diffusion occurred due to the inter-ionic attraction and molecular association between the adsorbate (COD and BOD) and the active AC adsorbent sites [33,34]. The final phase (20–60 min) of the adsorption process is called equilibrium phase and has been associated with the attainment of equilibrium with slow adsorption rate due to the decreasing the active AC sites as well as the concentration of COD and BOD [33,34].

3.3.3 Kinetic Modeling of Adsorption Process

Figure 5 presents the linear plots of the PFO and PSO kinetics models for the removals of COD and BOD. The kinetic parameters calculated from the linear plots are presented in Table 2. For the PFO model, $q_{e,cal}$ was found to be 31.9 mg/g for COD which is significantly less than the $q_{e,exp}$ value of 52.2 mg/g. On the contrary, $q_{e,cal}$ was found to be 29.6 mg/g for BOD which was in close agreement with the $q_{e,exp}$ value of 31.9 mg/g. As shown in Table 2, the PFO reaction rate constant (k_1) was found to be 0.15/min for COD and 0.17/min for BOD with high coefficient of determination (R^2) values of 0.90 and 0.97, respectively. The values of $q_{e,cal}$ obtained from the PSO model were estimated as 52.68 mg/g for COD and 30.67 mg/g for BOD. These values are in close agreement with $q_{e,exp}$ values of 52.20 mg/g for COD and 28.20 mg/g

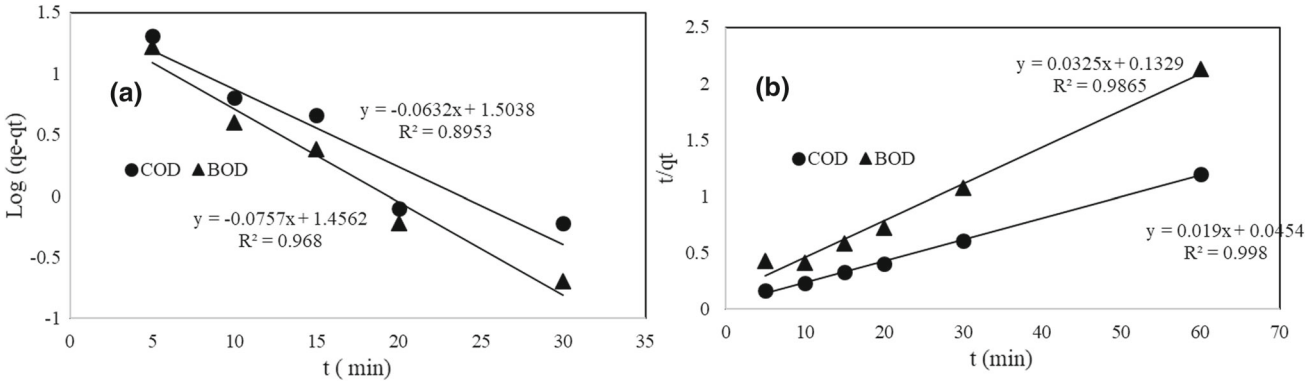

Fig. 5 linear plots of **a** pseudo-first-order and **b** pseudo-second-order kinetics models for the adsorption of COD and BOD on to AC. AC dose 0.2 mg/L, pH = 7.0–7.8, temperature 25 °C, COD = 35 mg/L and BOD = 23.4 mg/L

Table 2 kinetic parameters pseudo-first-order and pseudo-second-order models for the adsorption of COD and BOD on the AC

Kinetics models	Parameters	COD	BOD
Experimental	$q_{e,exp}$ (mg/g)	50.20	28.20
Pseudo-first order	$q_{e,cal}$ (mg/g)	31.90	29.57
	k_1 (/min)	0.15	0.17
	R^2	0.90	0.97
Pseudo-second order	$q_{e,.cal}$ (mg/g)	52.68	30.76
	k_2 [(g/mg/min)]	7.93E−03	7.95E−03
	R^2	0.99	0.98

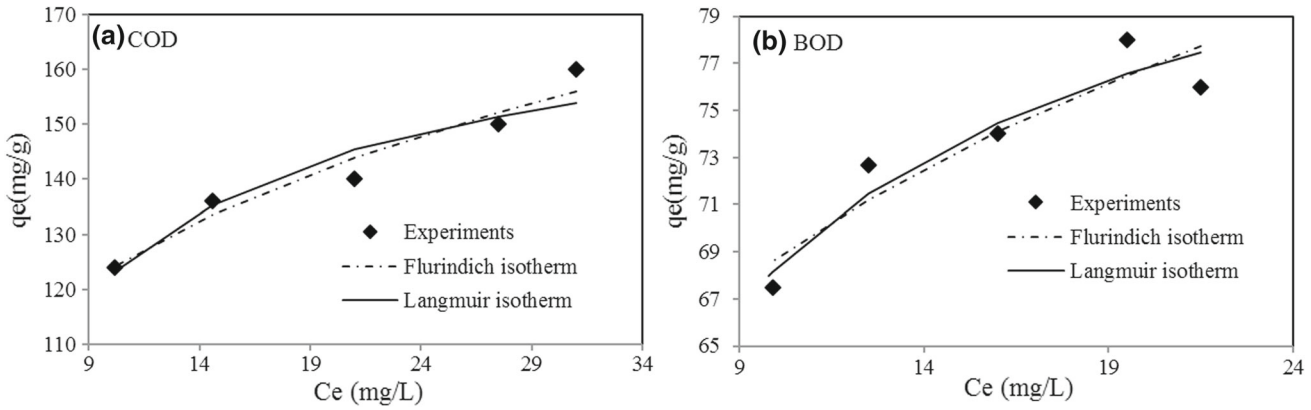

Fig. 6 Langmuir and Freundlich isotherm curves for adsorption of **a** COD and **b** BOD on the AC. AC dose 0.025–0.2 mg/L, pH 7.0–7.8, temperature 25 °C, COD 35 mg/L and BOD 23.4 mg/L

Table 3 Langmuir and Freundlich isotherm models parameters for the adsorption of COD and BOD on the AC

Water quality parameter	Langmuir isotherm				Freundlich isotherm			
	q_o (mg/g)	k_L (L/mg)	R_L	R^2	k_f (mg/g)	$1/n$	n	R^2
COD	175	0.23	0.11	0.93	77	0.21	4.86	0.95
BOD	88	0.35	0.11	0.91	47	0.16	6.21	0.87

for BOD. The second-order reaction rate constant (k_2) of PSO model for the COD and BOD was estimated as 0.00793 and 0.00795 g/mg/min with high coefficient of determination (R^2) values of 0.99 and 0.98.

Higher values of R^2 for both the COD and BOD obtained from the PSO model suggest that PSO kinetic model is the best fit for adsorption kinetic data and should be used to characterize the kinetics of COD and BOD adsorption. Hence, adsorption of COD and BOD onto the AC is primarily controlled by chemisorption rate-controlling mechanism. A higher value of R^2 (0.97) in PFO model for BOD also recommends that the adsorption of BOD might occasionally be dependent on the concentration of BOD in the AGW [34].

3.3.4 Adsorption Isotherm Modeling

Figure 6 presents the Langmuir and Freundlich isotherm curves for the adsorption of COD and BOD on the AC. All of the isotherm curves obtained are typical "L"-shaped curves (see Fig. 6). These findings indicate that both the COD and BOD have high adsorption affinity on the AC surface. Table 3 presents the isotherm parameters of Langmuir and Freundlich models obtained in this study. Langmuir isotherm parameters for COD and BOD were calculated from the linear plot of C_e/q_e versus C_e of the experimental data, whereas a linear plot of log q_e versus log C_e was used to calculate the Freundlich isotherm parameters.

Based on the R^2 values obtained for COD and BOD in both the isotherms models (> 0.87), it can be demonstrated that both the models are appropriate to characterize the adsorption of COD and BOD on activated carbon. For Langmuir models, the maximum adsorption capacity (q_o) was calculated to be 175 mg/g for COD and 88 mg/g for BOD. K_L values were 0.23 and 0.35 L/mg with coefficient of determination of 0.93 for COD and 0.91 for BOD. Estimated R_L value of 0.11 for both COD and BOD indicates favorable monolayer and homogeneous adsorption on to the AC. For Freundlich isotherm, the constants k_f and n were estimated as 77 mg/g

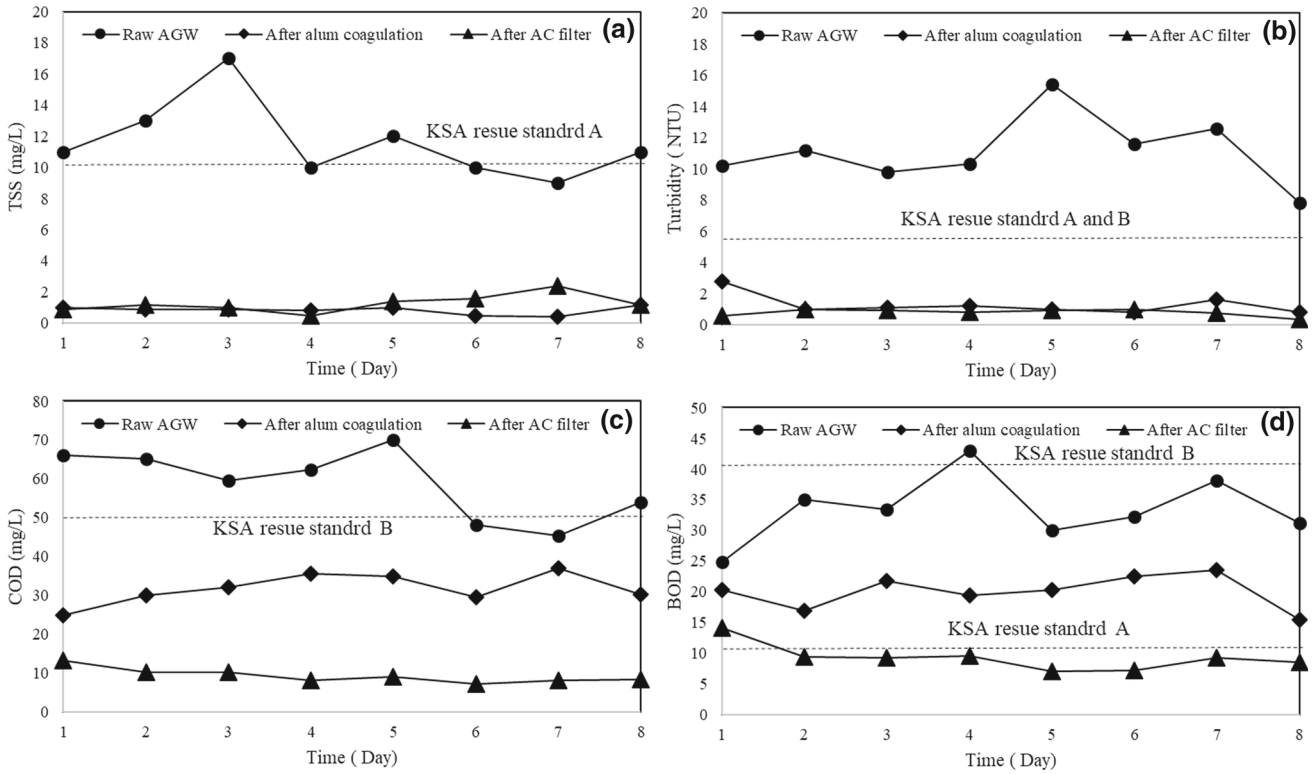

Fig. 7 Concentrations of **a** TSS, **b** turbidity, **c** COD and **d** BOD in the raw AGW, after alum coagulation and in the effluent of AC filter. KSA Standard A for unrestricted irrigation, toilet flushing, street and pedestrian, and firefighting [30] and KSA Standard B for restricted irrigation [30]

and 4.86 for COD and 47 mg/g and 6.21 for BOD with R^2 values of 0.95 and 0.87, respectively. The n values greater then unity indicate a favorable multilayer adsorption on the AC.

3.4 Laboratory-Scale Continuous Treatment Experiments

The laboratory-scale continuous experiments were conducted at pH ranging between 7.2 and 8.0 and room temperature of 25 °C. The pH values varied between 7.5 and 8.0 in the coagulation tank and between 7.2 and 8.0 in the effluent of AC adoption column which remained consistent throughout the experiments. Figure 7a–d presents the removal performance of TSS, turbidity, COD, and BOD after coagulation tank and at the effluent of AC adsorption column. Efficient removals of TSS and turbidity were observed at the coagulation stage archiving less than 1 mg/L of TSS and less than 1 NTU turbidity. These results were distinctly below the reuse standards of KSA for all potential reuse applications, including restricted and unrestricted irrigation, toilet flushing, street cleaning, and firefighting. In the effluent of AC adsorption column, residual TSS and turbidity remained consistent, i.e., less than 1 mg/L and 1 NTU.

These observations indicate that neither the suspended particles nor the colloidal particles released from the AC adsorption column. Coagulation stage was not found efficient achieving around 30 mg/L of COD and 20 mg/L of BOD removals. These values were below the KSA reuse standard of restricted irrigation but considerably higher than the standard values for unrestricted irrigation, toilet flushing, street cleaning, and firefighting. However, efficient removals of COD and BOD were observed at the AC adsorption stage achieving < 10 mg/L COD and BOD at the effluent of AC column throughout the operation. These values are below the KSA standard values for unrestricted irrigation, toilet flushing, street cleaning, and firefighting.

As for the biological contaminants shown in Table 1, levels of both the TC and FC were found to be higher than that of the KSA standard threshold for recycling. Although the disinfection process was not examined in this study, based on the findings of a previous study [6] it can be presumed that biological contaminants (total coliform, fecal coliform, and E-coil) can be effectively eliminated from AGW through conventional chlorination practice.

3.5 Full-Scale Treatment Process and Economic Feasibility Study

The details of a coagulation tank and AC adsorption column for full-scale treatment process treating a typical daily AGW of 1500 L/day from a medium-sized mosque in KSA are pre-

Table 4 Calculated design parameters of the coagulation tank and AC column filter with chemical consumption cost of the proposed treatment process in this study

Parameters	Coagulation tank	AC column
Influent concentration (mg/L)	33.5	20.0
Effluent concentration (mg/L)	20.0	9.3
% removal	40.18	53.50
AGW flow rate (L/day)	1500	1500
EBCT or HRT (min)	20	35
Volume (m^3)	0.021	0.036
Diameter (cm)	15	15
Depth (cm)	30	52
q_o(kg/kg) (Langmuir isotherm model)	–	0.09
Alum dose (mg/L) (coagulation experiments)	20	–
Mass required (kg)	–	13.56
Run time (day)	–	40
Mass required per day (kg/day)	0.03	0.34
Alum or AC consumption cost (US$/$m^3$)	0.04	0.11

sented in Table 4. The calculations are based on the BOD removal parameters obtained from coagulation experiments, adsorption isotherm models, and continuous experiments presented earlier. Based on the AGW daily flow rate of 1500 L/day and mixing time (HRT) of 20 min in coagulation experiments, the diameter of the 30 cm deep coagulation tank was estimated as 15 cm. The estimated daily alum consumption was 0.03 kg/day using optimum alum dose of 20 mg/L. By using 35 min empty bed contact time (EBCT) obtained from continuous experiments and daily flow rate of 1500 L/day, the diameter of 52 cm deep AC adsorption column was found to be 15 cm. Maximum BOD adsorption capacity q_o (i.e., 88 mg/g) from the Langmuir isotherm model was used to calculate the daily AC consumption rate of 0.34 kg/day. Following the AC adsorption column, a disinfection unit with the AGW treatment steam is necessary for the removal of bacteria. It is recommended that a full-scale AGW treatment process would consist of a storage or equalization tank connected to a coagulation tank followed by an AC adsorption column, and finally a disinfection tank for removal of pathogens from AGW.

Total production cost for treating 1 m^3 of AGW (US $/$m^3$) was estimated based on the annualized capital cost, chemical consumption (Alum and AC) cost, and operating (energy) cost [35]. The total cost for a full-scale treatment process was estimated to be 1.02 US$/$m^3$ which is broken down into 0.59 US$ capital (or investment cost), 0.28 US$ operational cost, and 0.15 US$ chemical consumption cost. The total AGW treatment cost is below the current water production cost in KSA of about 1.09 USD/m^3 [1]. The estimated total daily AGW production from 100,000 mosques (excluded two holy mosques) in KSA is 150,000 m^3/day. Therefore, by implementing the proposed treatment process all over the KSA can save around 3,850,000 US$ annually.

In addition, such reuse practices will reduce the existing groundwater withdrawals (or consumption of desalinated water) and will be an ambitious step toward sustainable development in line with the KSA Vision 2030. The present study provides a useful insight into the technical and economic feasibility of treating AGW using alum coagulation and AC adsorption.

4 Summary and Conclusions

This study showed that the combination of alum coagulation followed by AC adsorption is an economically feasible and effective option for the treatment of AGW. In coagulation experiments, around 96% removal of turbidity, 32% removal of COD, and 50% removal of BOD (50%) were achieved at 20 mg/L of optimal alum dose, whereas in AC adsorption experiments, overall COD removal of 71% and BOD removal of 57% were achieved at 20 min adsorption equilibrium time and at 0.2 g/L of AC dose.

The adsorption kinetic data for both the COD and BOD were best fitted to a pseudo-second-order kinetics model with high R^2 value of 0.98. Both Langmuir and Freundlich isotherm models were found to be appropriate to describe the adsorption of COD and BOD on to AC. From the Langmuir model, maximum adsorption capacities were calculated as 175 and 88 mg/g, respectively, for COD and BOD.

Continuous experiments showed that the effluent of coagulation tank achieved less than 1 NTU of turbidity, < 1 mg/L of TSS, 20 mg/L of COD, and 10 mg/L of BOD at 20 min HRT. Residual COD and BOD were further reduced to less than 10 mg/L at the effluent of AC adsorption column at 35 min EBCT. The quality of treated AGW through continuous experiments was found suitable for potential recycling

applications, including unrestricted irrigation, toilet flushing, and firefighting.

Economic feasibility study showed that the total cost for treating per m^3 of AGW was estimated to be less than the current cost of water production in KSA. The findings of the present investigation provide basis for design guidelines for further full-scale treatability studies for reuse of AGW in arid and semiarid regions, such as KSA and rest of Gulf countries. It is recommended that future research should conduct long-term continuous experiments to investigate the breakthrough curve of the AC adsorption column for getting more insights into full-scale treatment process.

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