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Feasibility study of coagulation system for greywater treatment and comparison of economical effects with those of electrocoagulation in mining areas

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Original Article

Abstract

Coagulants exert a significant influence on removing turbidity, TSS and COD. This study has examined the effects of poly-aluminium chloride (PAC), aluminium sulphate (alum) and ferric chloride on removal of turbidity, TSS, COD from greywater in residential complexes of miners working in decorative stone mines. Also, a comparison was undertaken with the electrocoagulation system to find out whether it was economical. Samples were collected over three days from the outlet pipes of greywater in the downstream of a village. The samples were sent to the laboratory to measure their organic materials. However, the Jar test was implemented by using all three coagulants, at concentrations of 100 to 1200 ppm. The results illustrate that the highest percentage of turbidity, COD and TSS removal were 98.24%, 94% and 77.25% respectively, which are related to PAC coagulant. The lowest cost to remove the organic materials in the coagulation method was harvested US \$ 0.09/m^3 for alum and howbeit. The cost for electrocoagulation method yielded US \$ 0.05/m^3 water.

KEYWORDS: Electrocoagulation, Coagulation, Greywater treatment, Mining areas.

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Introduction

Greywater or sludge is all wastewater generated by households or office buildings in mines from streams, without faecal contamination i.e. all streams except for the wastewater from toilets. Sources of greywater include e.g. sinks, showers, baths, clothes or dishwashers. The application of greywater reuse in mine systems provides substantial benefits to both the water supply subsystem, by reducing the demand for fresh clean water, as well as the wastewater subsystems, by reducing the amount of wastewater required to be conveyed and treated. Greywater discharge results exert influence on public health and the environment. Soil and groundwater pollution and damage to crops are caused by high concentrations of boron, sodium or surfactants, some of which may not be biodegradable.[1] Greywater is defined as municipal wastewater which contains water in baths, showers, tubs, ponds, dishwashers, washing machines and kitchen sinks, but not toilet water.[2–4] The proper utilization of recycled wastewater for toilet flushing, washing windows and garden irrigation is a desirable way to reduce the consumption of drinking water in households.[5, 6]

The dearth of water resources is a global concern, which can have a serious influence on people's lives. Water is an important element for economic development and political stability, while shortage of water resources is a very important barrier to the development of agriculture.[7, 8] Therefore, in different countries, reuse of wastewater is rapidly expanding in order to irrigate the majority of agricultural projects with this water.[9]

Natural water sources often include several dissolved and suspended contaminants. Large and suspended particles in water, such as sand

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and gravel, are easily removed from water as small and separated units in filtration and settling processes. Smaller particles—commonly called colloids—can be removed only after coagulation and flocculation operations. Thus, colloidal particles gradually stick together, making larger particles.[10] The size of colloidal particles which are exhibited in water ranging from 1 to 0.001 microns, while the settling rate of a particle with a diameter of 0.1 micron is about 3 m in a million years. So, it is inconceivable to filter water without the utilization of substances that increase the settling rate of colloidal particles.[11]

The process of coagulation has been known as a pre-process that completes filtration. In this process, coagulants make coarser particles in water and these particles are separated from the water by sedimentation or filtration processes. Basically, metal salts like alum, ferric sulphate, ferrous sulphate, ferric chloride, anionic cationic and non-ion organic polymers are called coagulants.

The literature review of the coagulant process is ancient: Egyptians used alum in 2000 BC.[12] Hence, these changes introduced coagulation as a pre-process to complete the filtration. Fundamentally, metal salts such as alum, ferric sulphate, ferrous sulphate, ferric chloride, anionic, cationic and non-ionic organic polymers are coagulants that can make sodium silicate, calcium carbonate, bentonite and sodium aluminate.[12] Recently, aluminium polymers such as poly-aluminium chloride (PAC) have been applied for coagulation and flocculation in the water and wastewater industry as they are available and entail reasonable costs. The researchers claimed that these products, in comparison with conventional coagulants, have many advantages like removal of suspended solids and organic matters, and reduction of environment alkalinity by reason of neutrality of compounds and less sludge production.[13] In previous studies, domestic sewage from an office building with ferric chloride coagulant, COD and TSS were measured as 240 mg/l and 45mg/l respectively. According to the reports, the optimal dosage of coagulant was 22mg/l, which eliminated 56% of COD and 89% of TSS.[14] Chengjin and colleagues applied PAC coagulant to oil pollution in 2015. The results displayed total dosages of the coagulant used could remove more than 96% of turbidity.[15] In addition, PAC and ferric chloride have the ability to remove more than 90 per cent of TSS, COD.[12, 13]

The electrocoagulation process can be used in a wide range of water and wastewater treatment systems. It is effective in the removal of inorganic contaminants and pathogens.[16] It should be noted that the electrocoagulation process is unstable, making suspended particles and contaminants in an aqueous medium neutral through an electric current.[17]

The pH, pollutant type and concentration, bubble size and position, floc stability, and agglomerate size, all influence the operation of the electrocoagulation unit. The overall mechanism is a combination of mechanisms functioning synergistically. The dominant mechanism may vary throughout the dynamic process as the reaction progresses, and shift with changes in operating parameters and pollutant types.

Reuse and reclamation of wastewater have been assessed in many researches that aimed to designate quality criteria, including turbidity, chemical oxygen demand (COD) and total suspended solids (TSS). The aim of this research was to handle the coagulation system to remove turbidity, COD and TSS, and to make these Economically analogous with the electrocoagulation system.

Coagulants mechanism

In this study, the coagulant mechanism—like alum, ferric chloride and PAC activities—have been discussed. When a coagulant is added to the water, some of it is implemented to adjust the electrical potential of particles and some is blended with the water alkalinity.

With increscent alum in water, the following reaction is shown in Eq. (1):

$$Al_2(SO_4) + 6H_2O \leftrightarrow 2Al(OH)_3 + 3H_2SO_4 \quad (1)$$

In addition to producing viscous aluminium hydroxide, which removes a number of suspended particles in the environment, the acid produced is combined with water alkalinity.[11, 12]

With increscent ferric chloride in the water, the reaction theory explains the following equation:

$$FeCl_3 + 3H_2O \leftrightarrow Fe(OH)_3 + 3HCl \quad (2)$$

Regarding PAC, it can be stated that poly-aluminium chloride or hydrate aluminium chloride is a mineral macro molecule, with monomers of two nuclear complexes of aluminium. This combination makes multi-core complexes at low concentrations and in the aqueous medium, which benefits from unique abilities. It has a polymeric structure with a general formula:

$[Al_2(OH)_{6-x}Cl_x.YH_2O]_z$ (3)

Aluminium hydrate reacts with hydrochloric acid in accordance with the following reaction, as denoted in Eq. (4)

$2Al(OH)_3 + nHCl \rightarrow Al_2(OH)_nCl_{6-n} + H_2O$ (4)

In poly-aluminium chloride molecules, polymeric aluminium includes hydroxide, chloride and some kinds of sulphates, and inorganic salts such as K, Ca, Mg and Na. A small part of aluminium sulphate appears as a monomer, in opposite to the main part of aluminium in PAC molecule clear in large polymer formation of Aligomers of Al_{13} cations $[Al_{12}(OH)_{24}AlO_4(H_2O)_{12}]^{+7}$. A solution pH is ranged 3.5 to 5 with 1% PAC in water. Flocculants normally appear better in size and with a magnified influence than coagulants due to the higher molecular weight. In some cases, however, the single utilization of flocculant is also ineffectual. The principal proof is that the interaction between the flocculant and particle is too weak, or there is a repellent force between the flocculant cycle and the particle surface. Hence, it is improved when the particles are treated with the coagulant process.[12]

This study was conducted in the laboratory by using Jar test equipment on greywater near mining areas located in South Khorasan province. A total of twenty-one samples was collected from greywater. Aluminium chloride , aluminium sulphate and ferric chloride were evaluated as coagulants at 100ppm to 1200ppm concentration. Six beakers were selected and in each was poured one litre of the tested sample, with certain COD and TSS and turbidity. Coagulants with an equal volume were poured in one to five beakers and one was kept empty as a control item. The sample was then discharged in a container into the Jar test device and rapid mixing was carried out at a speed of 170 rpm for one minute and gentle mixing at 40 rpm for 20 minutes. After gentle mixing, the sample was transferred to sedimentation tank in static situations for 20 minutes. Figure 1 underscores the elimination of organic matter by coagulation. After testing and through measuring BOD, COD and TSS and turbidity, the best coagulant was determined.

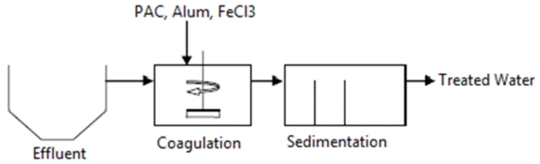

Figure 1. Schematic diagram of the pilot scale plant

Materials and Methods

Wastewater resource and its characteristics

In this research, the characteristics of greywater of mine and Fanud village, which agglomerated in ponds around the mining areas, were investigated. It is located 40 kilometres southeast of Birjand city in eastern Iran, and has a population of around 1,000, most of whom work in mines. Wastewater samples were collected from the pipes that discharge greywater with 5 m^3/h based on Tablel.

Sampling and selection of equipment

The physical and chemical properties of wastewater, along with greywater reuse standards, have been mentioned in Table 1 Coagulants utilized in this research are poly-aluminium chloride, aluminium sulphate and ferric chloride, provided by Merck Company in Germany. The initial tests were implemented on samples transported to the laboratory in order to ascertain the turbidity,. COD, pH, and TSS. Thus, the COD parameter was measured by using return distillation method with potassium dichromate. Turbidity was analysed through UV-VIS

Table 1. Standards for greywater reuse in different countries and contents in entrance greywater

Parameter	pH	TSS (mg/l)	Turbidity (NTU)	BOD5 (mg/l)	COD (mg/l)
Germany[18]	-	-	-	5	-
China[19]	6–9	-	<5	<6	-
USA[20]	6–9	-	<2	10	-
Japan[21]	5.8–8.6	-	≤5	≤3	-
Queensland[22]	-	30	-	-	-
Slovenia[23]	6.5–9	-	-	30	200
Input in this study	6.48	59	17.1	210	700

spectrophotometer (SHIMADZU) while pH was measured by Siberscan pH meter in pc 300 model.

Results and Discussion

Turbidity removal

Jar tests were executed to ascertain the best concentration of the coagulant. Since the concentration of coagulants has a great impact on the removal of turbidity of greywater sewage, turbidity can be removed to 90% with different levels of coagulants.[24] In this research, the effects of 100ppm to 1200ppm concentrations were estimated on turbidity removal by Jar tests. The percentage of turbidity removal for PAC, alum and ferric chloride has been demonstrated in Figure 2. As can be seen, since greywater entrance includes turbidity equal to 17/1 NTU, PAC at 1200 ppm concentration could remove 98.24 per cent of turbidity. When it is compared with Gokhan Erkrem Ustun and Colleagues' (2011) study, it could eliminate 90% of turbidity, whereas our work yielded a higher percentage of turbidity.[25]

Alum—solely at a concentration of 1200ppm—could remove 81.75% of turbidity. When it is compared with YX Zhaoa and colleagues' (2010) study, in which 87% of turbidity was removed, our results depicted a smaller percentage of turbidity removal.[26]

Ferric chloride has only removed a small percentage of turbidity, and with increasing concentrations of coagulant, no change has been deciphered in the removal of turbidity. Ferric chloride—at a concentration of 1200ppm—could remove 28.24% of turbidity. Thus, the efficiency of turbidity removal with ferric chloride cannot reduce the turbidity removal believable. Gokhan Erkrem Ustun et al. (2011) could eliminate 70% of turbidity, whereas our research showed a much smaller percentage of turbidity removal.[25]

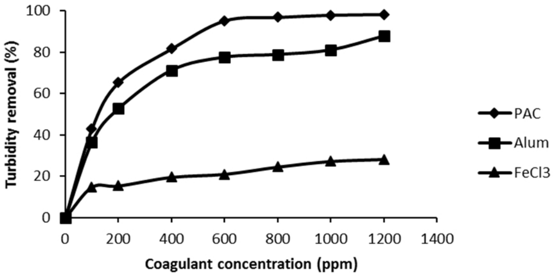

Figure 2. The consequences of the Jar test in the interval of turbidity removal for different PAC, Alum, $FeCl_3$ concentrations

COD removal

Since the concentration of coagulants affects COD removal, COD removal increased up to 80% and even higher.[27] In this study, the impact of concentrations of 100 ppm to 1200 ppm on COD removal was evaluated by Jar tests. COD removal percentages for PAC, alum and ferric chloride have been represented in Figure 3 and COD input equals to 700mg/l. As was mentioned, the higher the concentrations of coagulant, the more COD removal percentage displayed, so that the efficiency of removal at concentration of 1000ppm PAC achieved 93% and then, with increscent PAC concentrations, no significant change was acquired in COD removal. Similar to PAC, the process for alum is the same such that at a concentration of 1200 ppm, removal efficiency of alum achieved 90%. Then, as concentration increased, no significant change was seen in the COD removal. Moreover, for ferric chloride at 800 ppm concentration, the removal efficiency reached 87%. Then, with increasing concentrations of coagulant, no significant change was observed in the COD removal.

According to Figure 3, it could be seen that the PAC could remove 94% of COD at concentrations of 1200ppm. Therefore, after comparing with the conclusions of Gokhan Erkrem Ustun et al. (2011), where 40% of COD was removed, in this study a significant percentage of COD was removed.[25]

In Figure 3, at a concentration of 1200ppm, alum could remove 90% of COD while according to the results of Georgia Antonopoulou et al. (2013), in which 81% of COD was removed, this study could remove a greater percentage of the COD.[25]

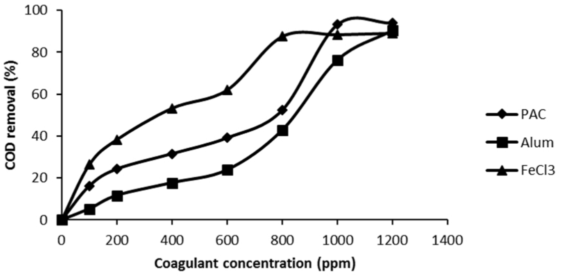

Figure 3. The consequences of the Jar test in the interval of COD removal for different PAC, Alum, FeCl3 concentrations

Ferric chloride could also remove 89.14% of COD. When compared with Georgia

Antonopoulou et al.'s (2013) conclusions, it is found that 81% of COD could be removed, which is a higher percentage of COD removal.[27]

TSS removal

It should be noted that the concentration of coagulants significantly influenced TSS removal to 80%.[27] In this study, concentrations of 100ppm to 1200ppm on TSS removal were handled by Jar tests. TSS removal percentages for PAC, alum and ferric chloride have been illustrated in Figure 4.

PAC at concentrations of 1200 ppm removed 77.25% (273 ppm) of the TSS. Alum, also at 1200 PPM concentration, could remove 68.38% (379.44 ppm) of TSS, and when it is compared to Georgia Antonopoulou et al.'s (2013) results, 79% of TSS was removed, so a smaller percentage of the TSS was removed.[27] In the case of ferric chloride, the process is similar to the PAC and alum. In fact, 66.35% of the TSS was removed at concentrations of 1200PPM. Besides, Georgia Antonopoulou et al. (2013) managed to remove 65% of the TSS.[27]

pH effect

Alum and ferric chloride coagulants have been known as bronsted acids and, by adding proton in the solutions, pH value was lowered.[28] The effect of different dosages of coagulants on domestic pH sewage was depicted in Figure 5.

By adding 100 to 1200 ppm of PAC coagulant, pH value enhanced with a relatively small variation from 6.7 to 6.12. No substantial difference was established in pH value. For alum in these concentrations, more pH changes were revealed from 3.8 to 5.6 and in case of ferric chloride, pH value increased from 2.17 to 3.7. According to investigations conducted by Davis (2010), it can be stated that the optimum pH for coagulation with ferric chloride have been observed between 6 and 9 and with alum between 5 and 9.[29]

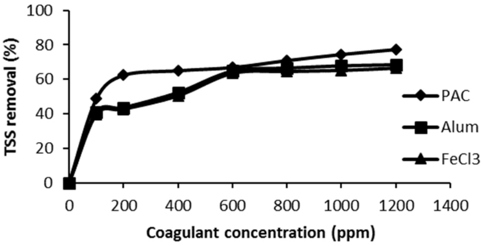

Figure 4: The consequences of the Jar test in the interval of TSS removal for different concentrations of PAC, Alum, FeCl3

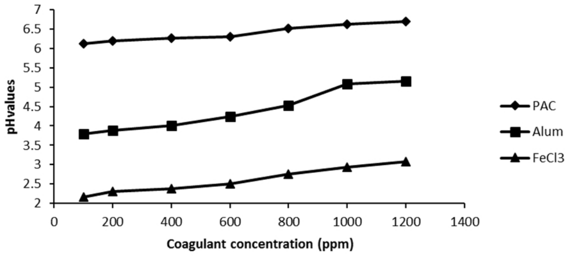

Figure 5: Effects of different PAC, Alum, FeCl3 concentrations (ppm) pH value

Economic evaluation of coagulation and electrocoagulation processes

The estimated cost is an important aspect of wastewater treatment. General expenses are defined by total capital costs as well as operating and maintenance costs. For a full-scale system, the cost depends on the nature and concentration of pollutants, wastewater flow rate, and configuration of devices.[30–32] Given the current situations for both coagulation and electro-coagulation systems, the estimated cost of this section was rendered with respect to the operating costs of the treatment. Electrocoagulation processes are assessed with respect to the effect of electrical potential (5 to 30V) and operation time (5 to 30min) for aluminium, iron and steel electrodes on greywater.

The consequences of the estimation of operating costs have been exhibited in Table 2. Since this water is reused in agricultural consumption, so turbidity, COD and TSS are less than 5 NTU, 200 mg/l and 30 mg/ l which have been considered the standard condition for all proposed costs. The price of water in the distribution area yielded US \$ 0.51/m^3 of water. Results depicted that the cost to overtake the minimum standard for PAC, aluminium and ferric chloride were measured 78%, 17% and 39% of water cost respectively. To achieve maximum efficiency, costs of PAC, alum and ferric chloride were harvested 88%, 43% and 47% of the water cost respectively. The applied wastewater in irrigation is a low value and an effective alternative for small irrigation areas, and it is very problematic to supply water for irrigation purposes. This suggests that the reuse of greywater as irrigation water is more economical. In a case study conducted by Gokhan et al. (2011), the input density yielded 0.24 m^3 per hour, in which SS, COD and turbidity removal were 64%, 39% and 81%

respectively. The cost of greywater reuse was proved to be US \$ 0.146/m^3 water.[25]

In Table 3, the cost of the coagulation used was compared with other methods. As can be shown, the minimum cost of coagulation is related to aluminium sulphate, which results in US \$ 0.09/m^3. This is clearly cheaper than the other methods referred to. By comparing this method with electrocoagulation, which has been assessed in this research, it should be noted that the cost of electrocoagulation to treat 1m^3 water is equivalent to US \$ 0.04. Electrocoagulation cost is relatively less than the coagulation method, but electrocoagulation is utilized for the following reasons:[33]

Table 2. The estimated treatment cost for the coagulation process.

NO.	Reagents	Basis	Unit cost (\$ US)	Treatment cost for maximum efficiency (US \$/m3)	Treatment cost for irrigation (US \$/m3)
1	PAC	Kg	0.43	0.43	0.38
2	Alum	Kg	0.17	0.2	0.07
3	Chloride Ferric	Kg	0.27	0.22	0.18
4	Electricity	Kw h^{-1}	0.02	0.02	0.02
5	Total treatment cost about PAC[a] (1,4)	US \$/m^3	_	0.45	0.4
6	Total treatment cost about Alum[a] (2,4)	US \$/m^3	_	0.22	0.09
7	Total treatment cost about $FeCl_3$[a] (3,4)	US \$/m^3	_	0.24	0.2

[a] Cost of labour and sludge disposal not included

1. In electrocoagulation process, oxidated sacrificial electrodes in wastewater streams need to changed
2. The utilization of electricity current could be noticeable in some countries.
3. In cathode electrodes, water-resistant oxide film may be shaped, which cause reduction of electrocoagulation yield
4. In this process, intense conductivity is required in wastewater suspension.
5. In some condition, gelatinous hydroxide could fall off to solubilize.

It should be noted that when TDS and EC of wastewater are high, the usage of electrocoagulation is not desirable.[34]

Since in the evaluated area, TDS and EC values were high, electrode and energy consumption increased. Therefore, it is recommended to utilize coagulation technique as a proper method for wastewater treatment in mining areas.

Table 3. Comparison of this with other cases in treatment method, flow rate, and unit cost

Location	Treatment facility	Flow rate (m^3/day)	Unit cost (US \$/m^3)
Germany [35]	Biological oxidation, microfiltration, UV	1	1.05
Fukuoka, Japan [36]	Biological oxidation, sand filtration, ozonation	8000	3.5
Tokyo, Japan [37]	Biological oxidation, ultrafiltration	180	1.8
Taipei, Taiwan [37]	Electrocoagulation	28	0.27
Turkey[25]	Coagulation	5.76	0.146
Iran (This study)	Coagulation by PAC	11.04	0.4
Iran (This study)	Coagulation by Alum	11.04	0.09
Iran (This study)	Coagulation by Chloride Ferric	11.04	0.2
Iran (This study)	Electrocoagulation	11.04	0.04

Conclusion

The method of greywater treatment in this area includes coagulation and sedimentation, which are used for reusing water to irrigate villages around the mines. For this purpose, physical and chemical parameters were designated, based on the output of greywater tests. The following results were obtained:

- With regard to the input analysis, COD, TSS and turbidity values were not suitable for application of agriculture irrigation guidelines.

- PAC and alum at the concentrations used can remove a high percentage of turbidity. But ferric chloride could not remove any optimal turbidity with any tested concentrations.

- All coagulants utilized in this study have the capability to remove a high percentage of COD at concentration of 1200ppm, which displays the highest removal percentage. PAC, alum and ferric chloride could remove 94%, 90.42% and 89.14% of COD respectively.

- To remove TSS in superb condition, PAC could remove 77.25% of the TSS, while the percentages obtained were 68.38% for alum and 66.35% for ferric chloride.

- The cost of water treatment to attain the maximum efficiency of PAC, alum and ferric chloride were 88%, 43% and 47% of the cost of irrigation water respectively.

- The cost of water treatment was obtained to achieve the minimum standard of the best cost for alum with 17% of the water cost

- The lowest investment in coagulation.

method is related to alum in which the cost of treatment for 1m3 water is equivalent to US $ 0.09. By comparing this method with electrocoagulation, it can be established that electrocoagulation treatment of 1m3 water (0.05 US $) entails a relatively low expenditure than coagulation process. Since in the evaluated area, TDS and EC values were high, electrode and energy consumption increased. Therefore, it is recommended that coagulation technique be utilized as a proper method for wastewater treatment in mining areas.

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