Pilot-Scale Electrocoagulation with Bipolar Aluminum Electrodes for On-Site Domestic Greywater Reuse

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Abstract: Designing a reclaimed water system provides an economically and environmentally favorable method for disposing of wastewater. However, some critical influences on on-site reclaimed water systems, such as limited building area, often limit the effectiveness of conventional treatment methods. This work established a compact and inexpensive electrocoagulation process with a capacity of 28 m^3/day to reclaim domestic greywater for human noncontact usage. The total unit cost of on-site domestic greywater reuse was U.S. \$0.27/m^3, which was below the local potable water rate. Moreover, the treatment facility required an area of 8 m^2. Both unit cost and required area in this work are lower than those reported in the literature. The experimental results support the feasibility of the on-site reuse of greywater in high-rise buildings.

CE Database subject headings: Aggregation; Coagulation; Water reuse; Water reclamation; Water treatment.

Introduction

Growing demand for fresh water resources has made municipal wastewater reuse an attractive method of conserving and even increasing available water supplies. Over 50% of the water demand from domestic and industrial applications could be met by water of lower quality than fully treated water, including applications such as process water, toilet flushing, garden water, and car washing (Dieter 1996). Substituting low-quality water for nonpotable purposes to preserve limited high-quality water resources is highly efficient and practical, especially in arid regions or developing countries.

Conventional reclaimed water treatment processes are effective in integrating secondary treatment with advanced treatment methods, such as microfiltration (MF), ultrafiltration (UF), reverse osmosis (RO), and chemical coagulation. However, such processes require a large serving area for treatment facilities and professional staff for operating and maintaining these treatment facilities. The electrocoagulation process offers an alternative to the aforementioned approaches that has the advantages of compactness and economic competitiveness.

Electrocoagulation has been reported to offer various advantages over conventional coagulation, specifically in relation to hydraulic retention time, removal efficiency of ultrafine particles, coagulant dosage, sludge production, cost, and operating and maintenance simplicity (Vik et al. 1984; Pouet and Grasmick 1995; Mills 2000). An extensive amount of literature has been published on electrocoagulation in conjunction with other processes, such as dissolved air flotation (Pouet and Casmick 1995), electroflotation (Chen et al. 2000), high gradient magnetic filtration (Tsouris et al. 2001), and the use of a settling tank (Jenke and Diebold 1984), to cope with various wastewater. Few works (Beck et al. 1974; Rubach and Saur 1997) have been reported on the electrocoagulation process that directly caused colloids to be floated by hydrogen bubbles generated in the cathodes by the electrolysis of water.

This investigation developed a pilot-scale electrocoagulation process combined with direct flotation by hydrogen gas evolution in the cathodes for reclaiming domestic greywater that followed the general guidelines for water reuse for human noncontact usage. This work thus attempted to determine the total cost of the reclaimed water and the consequent payoff period. Furthermore, the proposed process was compared with other processes for greywater reuse in buildings described in the literature, with regard to both the serving area required by the treatment facility and the cost of the reclaimed water.

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Experimental Procedures

Description of Electrocoagulation Process

Fig. 1 displays the layout of the electrocoagulation process, occupying approximately 8 m^2 in total, for on-site domestic greywater reuse. The inlet greywater, drawn from a sinkhole, was fed
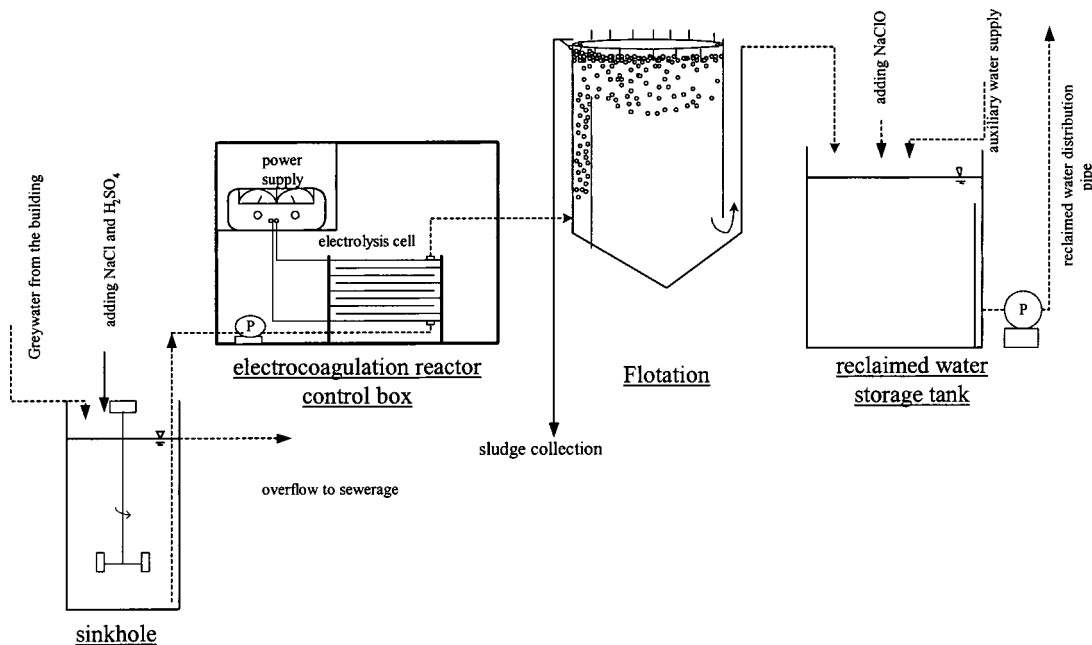
Fig. 1. Flow diagram of pilot-scale electrocoagulation process

to the electrolysis cell at 1.2–1.4 m^3/h, and NaCl (1M) and H$_2$SO$_4$ (1M) were added to adjust the conductivity to 500 ~ 600 µs/cm and the pH to 6–7, respectively. The electrolysis cell comprised a pair of outer stainless-steel monopolar electrodes and numerous inner aluminum bipolar electrodes (99% purity), without any electric connection. The dimensions of the reactor were determined according to our previous laboratory study (Lin et al. 2002). The interelectrode distance was 10 mm, and there were 20 horizontal-flow channels. Each plate had dimensions of 500 × 240 × 10 mm, with an effective area of 1,000 cm^2, given a flow velocity of 13.5 cm/s and a contact time of 70 s. This work used aluminum as the sacrificial anode, rather than iron, because the residual ferrous ions are easily oxidized by air in the storage tank, coloring the reclaimed water. Scum was then separated out using the flotation apparatus, and flotation was achieved by gas bubbles developed in the cathode within 15 min of hydraulic retention, where the top layer can be skimmed and clean water regularly tapped. The reclaimed water was disinfected with sodium hypochlorate (NaClO) in the reclaimed water tank, an auxiliary water supply was provided, and a residual chlorine of over 0.4 mg/L was maintained.

Characteristics of Domestic Greywater

The quality of the reclaimed water in the flotation unit effluent was assessed in terms of biological oxygen demand (BOD$_5$), pH, suspension solids (SS), total solids (TS), ammonia-nitrogen (NH$_3$-N), *E. coli*, residual chlorine, and chloride ion, all of which were measured using standard methods [American Public Health Association (APHA) 1992]. Chemical oxygen demand (COD) was measured using a COD reactor and a direct reading spectrophotometer (DR/2000, HACH), and the latter was also used to assess color, represented as visible absorbance at 420 nm. Furthermore, both turbidity and conductivity were measured using a turbidimeter (2100P, HACH) and a conductivity meter (LF96B, Suntex), respectively. A particle diameter of 0.45 µm was selected as the threshold for distinguishing soluble chemical oxygen demand (CODs) from total chemical oxygen demand (COD$_t$). Fur-

thermore, a granolumeter (M175, CILAS) was used to analyze the relative percentage of particles with diameters of under 196 µm.

Results and Discussion

### Effect of Applied Voltage on Pollutants Aggregation

Preliminary laboratory testing of the electrolysis cell involved determining the effect of applied voltage on the size distribution of particles with kaolinite suspensions as a turbidity source, using a granolumeter. Kaolinite suspensions with a small range of size distributions, namely, between 4 and 16 µm (Fig. 2), were used to simulate particle pollutants of greywater. As indicated in Fig. 2, applying an electric field from 50–255 V tended to increase the particle size in the effluent. Thus, the aggregation of particles, resulting from the charge redistribution on the particle surface in the electric field, would occur in all the range of 50–255 V. However, a little degree of change in the particle size was observed when the applied voltage was increased from 136–255 V. Regarding the effectiveness and economics of this system, it is suggested the use of the voltage be below 136 V.

Effect of Aluminum Release Dosage on Pollutants Removal

Eq. (1) expresses the theoretical aluminum concentration at the outlet of the electrolysis cell

$$C_{Al} = \frac{M_{total,Al}}{V_{total,liquid}} = \frac{I \times t \times m_{Al} \times N}{Q \times t} = \frac{I \times m_{Al} \times N}{Q} \quad (1)$$
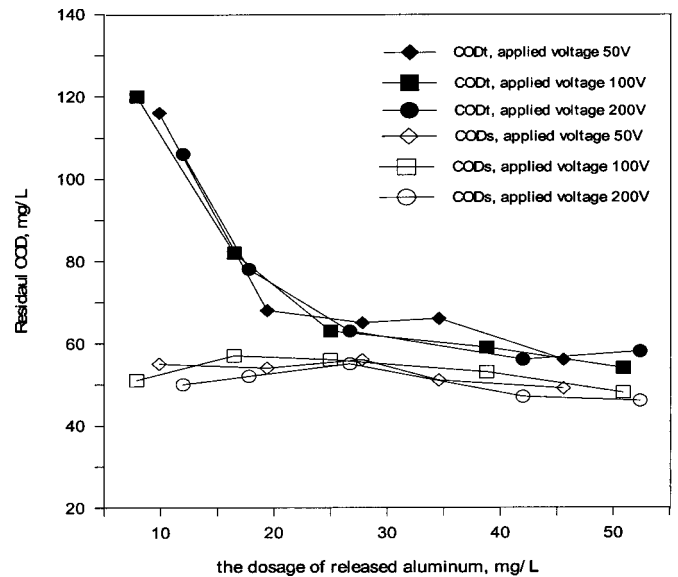
where C_{Al}=dosage of released aluminum from the outlet of the electrolysis cell (mg/L); $M_{total,Al}$=total mass of released aluminum (mg) by Faraday's law within the retention time (t, s.); $V_{total,liquid}$=total volume of the effluent (L) within the retention time: I=applied current (amperes); N=number of channels in the electrolysis cell; Q=flow rate (L/s), and m_{Al}=electrochemical
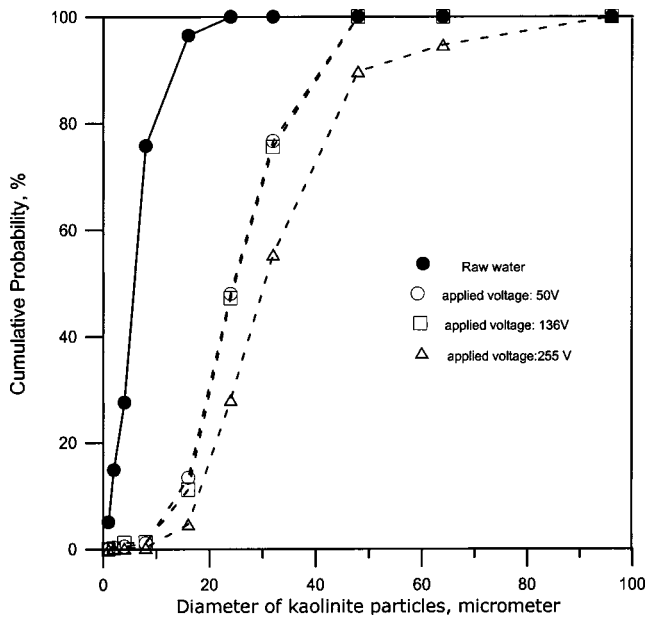
Fig. 2. Effect of applied voltage on size distribution of kaolinite suspensions: initial turbidity=410 NTU; flow rate=20 mL/s; applied current=0.65 A; number of channels=10; interelectrode distance=5 mm; pH=6.5; contact time=48 s; conductivity=423 μS/cm

Fig. 3. Effect of released aluminum dosage on residual COD; initial total COD=128 mg/L; initial soluble chemical oxygen demand (COD)=76 mg/L; flow rate=34 mL/s; number of channels=20; interelectrode distance=5 mm; pH=7.2; contact time=48 s

equivalent of aluminum (0.093 mg/C). Consequently, the dosage of released aluminum in the flux, like the dosage of coagulant in conventional coagulation, can be determined by adjusting the applied current and flow rate.

Given the constant flow rate, various dosages of released aluminum can be obtained by adjusting the applied current to evaluate the efficient dosage. Fig. 3 shows that residual COD_t declines as the dosage of released aluminum increased to 25 mg/L, regardless of the applied voltage, where an average of 60% COD_t removal was achieved. Raising the dosage of released aluminum to 50 mg/L did not increase COD_t removal efficiency. Meanwhile, no significant removal of residual COD_s was achieved.

COD removal efficiency was determined by the dosage of aluminum released and generally limited by the presence of soluble contaminants in the influent.

Reclaimed Water Quality

The key problem related to reclaimed water quality is to protect the public from pathogenic microorganisms. Moreover, the reclaimed water must also not be aesthetically objectionable (Asanon et al. 1996). Table 1 lists the parameters of the reclaimed water, which were monitored and considered in the light of guidelines developed for use in the United States, Japan, and China. The appearance, odor, and microorganism content of the re-

Table 1. Comparison of Reclaimed Water in Electrocoagulation Process with Reclaimed Water Quality Guidelines for Nonpotable Use

| Parameter	Raw water	Reclaimed water	Guidelines for reclaimed water quality for nonpotable use			
			Taiwan[a]	Japan[b]	United States[c]	China[d]
Turbidity (NTU)	20.1–120.0 (43.1)[e]	1.2–17 (3.6)	–	–	≦2	≦10
TS (mg/L)	350–450 (405)	350–400 (372)	–	–	–	–
SS (mg/L)	15–84 (29)	4–19 (9)	–	–	–	≦10
Color (AMID)	5	<1	≦40	Not unpleasant	–	≦30
Odor	-	Not unpleasant	Not unpleasant	Not unpleasant	–	Not unpleasant
pH	6.5–7.5	7.0–8.0	6.8–8.5	5.8–8.6	6.0–9.0	6.5–9.0
BOD_5 (mg/L)	10–41 (23)	5–16 (9)	≦10	–	≦10	≦10
COD (mg/L)	27–102 (55)	14–44 (22)	–	–	–	≦50
NH_3-N(mg/L)	0.145–0.148	0.006–0.007	–	–	–	≦20
Cl^- (mg/L)	180–230 (206)	154–178 (167)	–	–	–	≦350
Cl_2 residual (mg/L)	–	1.2–2.1 (1.5)	Trace amount	Trace amount	≧1.0	≧0.2
E. Coli (CFU/100 mL)	3,800–5,600 (5,100)	Not detected	≦10 (CFU/mL)	<1,000	Not detectable	≦3 CFU/L

[a]Adapted from Taiwan Architecture and Building Research Institute 1995 guidelines; for toilet flushing.

[b]Adapted from Japan Sewage Works Association 1993 guidelines; for toilet flushing.

[c]Adapted from USEPA 1992 guidelines for water reuse; for urban uses, irrigation of food crops eaten raw, recreational impounds.

[d]Adapted from Beijing, China, 1993 guidelines for water reuse; for toilet flushing.

[e]Average values are in parentheses.
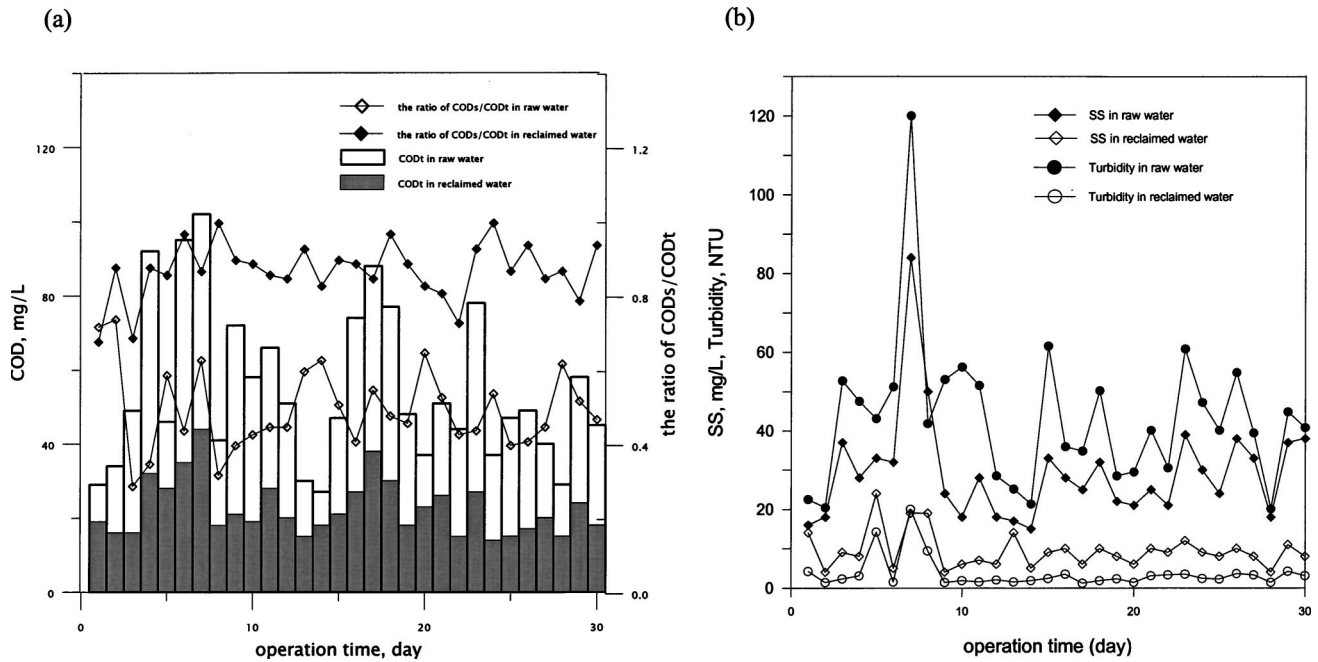
Fig. 4. Water quality of effluent from pilot-scale electrocoagulation process: (a) Chemical oxygen demand (COD) removal; (b) SS and turbidity. Operation conditions: released aluminum dosage=20 mg/L; applied voltage=150–160V; flow rate=20 L/min; number of channels=20; d =10 mm; pH=6.0; conductivity=720 μS/cm

Table 2. Estimated Cost for Pilot-Scale Electrocoagulation Process

Item	Cost (U.S. $/m^3)	Percentage (%)
Capital cost	0.08	29.6
Operational cost[a]		
Electric demand (0.8 kwh/m^3)	0.07	25.9
Aluminum plate consumption	0.04	14.8
Chemicals	0.02	7.4
Sludge treatment	0.06	22.3
Total operational cost	0.19	
Total unit cost	0.27	100

[a]Assuming a depreciation period of 10 years and an interest rate of 5%. The aluminum plate costs U.S. $2/kg, and electricity costs are U.S. $0.09/kwh. The quantity of wet sludge treated in the electrocoagulation process was 4.0–7.0 kg/m^3. The constant applied current is 3A, and the average applied voltage is 135V.

claimed water in the pilot-scale electrocoagulation process satisfied the general guidelines. As indicated in Fig. 4, the ratios of COD_s and COD_t ranged from 0.3 to 0.6 in the influent and from 0.8 to 1.0 in the effluent. Moreover, the COD_t of the effluent was related to the COD_s of the influent, suggesting that electrocoagulation easily removes particulate organic matter and slightly reduces soluble organic matter. Thus, suspension solids were easily removed from the solution at a high efficiency.

Reclaimed Water Cost

When optimized, the total cost for on-site domestic greywater reuse by electrocoagulation is U.S. $0.27/m^3 (Table 2). In this pilot site, the local average potable water rate is U.S. $0.3/m^3 and the operational cost of reclaiming water is U.S. $0.19/m^3. The use of reclaimed water to reduce demand for potable water achieves a direct economic benefit of U.S. $0.11/m^3, which is the difference between the cost of local potable water and the

Table 3. Comparison of This Work with Other Cases in Treatment Method, Flow Rate, Required Area, and Unit Cost

Location	Type of reclaimed water system	Treatment facility	Flow rate (m^3/day)	Purpose of reclaimed water	Serving space for treatment facility (m^2)	Unit cost (U.S. $/m^3)
Tokyo, Japan	Individual building	Biological oxidation, ultrafiltration	180	Toilet flushing	–	1.80
Germany[a]	Individual building	Biological oxidation, microfiltration, UV	1	Toilet flushing	–	1.05
Tokyo, Japan[b]	Individual building	Aeration tank, ultrafiltration	110	Toilet flushing	45	–
Tokyo, Japan[b]	Individual building	Biological oxidation, microfiltration	154	Toilet flushing	285	–
Fukuoka, Japan[c]	Regional dual water system	Biological oxidation, sand filtration, ozonation	8,000	Toilet flushing	–	3.5
Taipei, Taiwan	This study	Electrocoagulation	28	Toilet flushing	8	0.27

[a]Adapted from Dieter (1996).

[b]Adapted from Shiao and Chen (1994).

[c]Adapted from Asano et al. (1996).

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operational cost of water reclamation. Meanwhile, the payoff period is 5.5 years and is determined mainly by the difference between the costs of potable and reclaimed water.

Four cases of water reclamation systems in individual buildings and one case of a regional dual water system exist for comparison with the system presented here. Table 3 reveals that the unit cost of a regional dual water system exceeds that of a dual water system in an individual building. Reclaimed water obtained using the system presented in this work is cheaper than that obtained in similar cases. The most important advantage of the building-based dual water system is that the electrocoagulation process does not require a lot of space in such a system.

Conclusions

Electrocoagulation is a viable alternative for on-site reuse of greywater in individual buildings. COD removal efficiency was determined by the dosage of aluminum released and is generally restricted by the presence of soluble contaminants in the influent. Furthermore, this pilot-scale process reclaimed domestic greywater at 28 m^3/day, meeting the general guidelines for water in human noncontact usage. The cost was U.S. \$0.27/m^3, and the treatment facility required an area of 8 m^2. Utilizing water of appropriate quality reduces the difference between water and wastewater, helping them to be ultimately recognized as the same natural resource.

Acknowledgment

Notation

The following symbols are used in this paper:

C_{Al} = dosage of released aluminum from outlet of electrolysis cell (mg/L);

I = applied current (amperes);

$M_{total,Al}$ = total mass of released aluminum by Faraday's law within retention time (t) (mg);

m_{Al} = electrochemical equivalent of aluminum (0.093 mg/C);

N = number of channels in electrolysis cell;

Q = flow rate (L/s); and

$V_{total,liquid}$ = total volume of effluent within retention time (L).

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