

# Reduction of organic matter and trihalomethane formation potential in reclaimed water from treated industrial estate wastewater by coagulation

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## Abstract

Raw water from treated industrial estate wastewater in northern Thailand was used in jar-test coagulation experiments with variations of separate alum and ferric chloride dosages from 10 to 80 mg/L at pH conditions ranging from 5 to 6.5. Natural organic matter (NOM) surrogates and trihalomethane formation potential (THMFP) were determined to study their reduction. The obtained results showed that total organic carbon (TOC) were gradually reduced from the average value of about 6.1 mg/L to a level of about 4.0 mg/L by alum and ferric chloride dosages of approximately 40 mg/L. Moreover, dissolved organic carbon (DOC) were reduced from an average value of 5.1 mg/L to a level of about 4.0 mg/L by alum and ferric chloride dosages of approximately 40 mg/L. Specific ultraviolet absorption (SUVA) were decreased from an average value of approximately 4.7 L/mg-m to a level of about 2 L/mg-m by alum and ferric chloride dosages of approximately 20 mg/L. In addition, chlorine demands at 1-day reaction were the same as those of 7-day demands with a correlation coefficient of 0.98 ( $n = 10$ , correlation significant at the 0.01 level). Interestingly, chloroform of approximately 65 and 60% of total THMFP was found as the predominant THMFP species in treated industrial estate wastewater and reclaimed water, respectively, in comparison with other THM species. Maximum THMFP percentage removal of 25 and 28 by using alum and ferric chloride dosages of about 80 mg/L at pH 5.5 and 5 were obtained, respectively, at the examined conditions.

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**Keywords:** Alum; Ferric chloride; Trihalomethane formation potential (THMFP); Reclaimed water; TOC; Coagulation

## 1. Introduction

Today, water shortages are a major problem for many industrial estates in Thailand, especially for those industries located in the Bangkok metropolitan and highland areas. Furthermore, the government has made restrictions more stringent with regards to the withdrawal of ground water for industrial applications [1]. Accordingly, using reclaimed wastewater is one of the options that can help relieve this problem.

The industrial Estate, located in northern Thailand, is currently consuming more than 10,000 m<sup>3</sup> of water per day and is currently facing a water shortage problem. Hence, a plan for using reclaimed water from treated industrial estate wastewater has been designed to alleviate this problem. However, by relieving one problem, it may cause another since potentially carcinogenic substances such as trihalomethanes (THMs), are formed during water treatment processes.

THMs are the by-products of water chlorination. In the chlorination process, which is commonly used for disinfection, chlorine can react with humic substances in natural organic matter (NOM) to form THMs. THMs represent a structural variation of the methane molecule (CH<sub>4</sub>) in which hydrogen atoms are substituted by four halogen atoms (F,

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Cl, Br, or I). The most common species of THMs generally formed in the water supply are chloroform ( $\text{CHCl}_3$ ), bromodichloromethane ( $\text{CHBrCl}_2$ ), dibromochloromethane ( $\text{CHBr}_2\text{Cl}$ ) and bromoform ( $\text{CHBr}_3$ ). Chloroform ( $\text{CHCl}_3$ ), the most well known THM that had been discovered by Rook [2], may not only cause central nervous system depression, but may also cause hepatotoxicity, nephrotoxicity, teratogenicity and carcinogenicity. Thus, the USEPA has issued a maximum contaminant level (MCL) for THMs in US drinking water supplies. The current MCL for THMs is  $80 \mu\text{g/L}$  and may be lowered to  $40 \mu\text{g/L}$  in several years [3].

Due to the importance of NOM in forming THMs, studies on the nature of NOM and its removal are a familiar topic in water treatment research. Whilst NOM are both hydrophobic and hydrophilic in nature, hydrophobic acid, which consists of humic (aquatic humic) and fulvic acids that cause its natural color, is suspected to be the most problematic precursor to THMs [4]. Fulvic acids have a higher charge density and are less amenable to coagulation by charge neutralization [5]. Fulvic acids are also more prevalent and more soluble than humic acids. The specific ultraviolet absorption (SUVA) of fulvic acids at 254 nm ranges from 2.9 to  $4.3 \text{ L/mg m}$ , whereas for humic acids it ranges from 4.8 to  $7.4 \text{ L/mg m}$  [6].

NOM were characterized by nonspecific parameters depending on their ability to adsorb ultraviolet light (ultraviolet adsorption at wavelengths of 254 nm [UV-254]) by their organic content (total organic carbon, TOC, dissolved organic matter, DOC) or by their potential to form THMs [7]. Yoon et al. [8] reported average values of DOC and trihalomethane formation potential (THMFP) in five major rivers in Korea, which were approximately equal to  $3.3 \text{ mg/L}$  and  $123.9 \mu\text{g/L}$ , respectively. White et al. [9] studied natural organic matter and DBP formation potential in 17 water resources of different drinking water systems in Alaska. They found that the DOC of sample sets ranged between 1.3 and  $18 \text{ mg/L}$  with a mean of  $8.5 \text{ mg/L}$ , while the THMFP ranged from 37 to  $1050 \mu\text{g/L}$  with an average value of  $327 \mu\text{g/L}$ . Singer et al. [10] reported DOC in water samples in North Carolina (USA) with average values equal to  $4.7 \text{ mg/L}$ . Amy et al. [11] presented DOC in water samples from South Carolina, Ohio, Florida, Oklahoma, New York, Mississippi, and South Dakota (USA) with average values equal to  $7.1 \text{ mg/L}$ . Serodes et al. [12] studied the occurrence of THMs and haloacetic acids (HAAs) in experiential chlorinated waters of the Quebec City area, Canada. It noted that THMs were already present in waters used in the experiments, which consisted of flocculation, sedimentation, filtration and ozone, varying from 18 to  $49 \mu\text{g/L}$  and that chloroform was the predominant THM species.

Bauman and Stenstrom [13] evaluated the removal of organohalogen precursors in municipal reclaimed wastewater (Aqua II) from the city of San Diego, California (USA). The treatment consisted of ferric chloride coagulation, flocculation and filtration followed by disinfection, acidification, reverse osmosis and carbon adsorption. UV-254, non-volatile total organic car-

bon (NVTOC), total organic halide formation potential and THMFP of untreated filtered secondary effluent at Aqua II were  $0.15 \text{ l/cm}$ ,  $8.30 \text{ mg/L}$ ,  $1280$  and  $547.6 \mu\text{g/L}$ , respectively. Moreover, the predominant THMFP species was chloroform whilst dichlorobromoform, dibromochloroform and bromoform were found in minority. Galapate et al. [14] investigated the quality of treated industrial wastewater and the results presented showed that average values of UV-260 and DOC were  $0.134 \text{ l/cm}$  and  $13.9 \text{ mg/L}$ , respectively while THMFP of treated industrial wastewater ranged from 15 to  $211 \mu\text{g/L}$  with an average value of  $72 \mu\text{g/L}$ .

USEPA advocated the enhance coagulation and enhanced precipitative softening for waterworks to utilize as a guideline for complying with MCL [15]. Coagulation flocculation and filtration effectively removed approximately 46 and 35.1% of NVTOC and THMFP from the municipal wastewater, respectively [13]. Matilainen et al. [16] indicated that alum coagulation and clarification, disinfection, activated carbon filtration and post-chlorination could remove TOC in raw water from Lake Roine, Tempere, Finland, from average values 5.5 to  $2.9 \text{ mg/L}$  (approximately 47% removal).

Recently, studies on natural organic matter and THMFP have generally included only water for drinking water supply facilities [17,18]. There is a need to study the THMFP and the character of NOM in other types of water such as reused or reclaimed wastewater. This work investigates the NOM surrogates and THMFP in treated industrial estate wastewater and reclaimed water including their reduction by coagulation.

## 2. Materials and methods

### 2.1. Source of raw water samples

The selected industrial estate, located in northern Thailand, treats approximately  $10,000 \text{ m}^3/\text{day}$  of wastewater. Composite samples were collected between October 2002 and February 2003 from five sampling points at the periphery of the final polishing pond of the central wastewater treatment plant. Samples were collected in glass bottles with TFE-lined screw caps and preserved with sodium thiosulfate prior to storage at  $4^\circ\text{C}$ .

### 2.2. Analytical methods

Turbidity was directly measured using a HACH 2100, turbidity meter.

UV-254 was analyzed in accordance with *Standard Methods* 5910 B. (Ultraviolet absorption method) [19]. The samples were filtered through prewashed  $0.45 \mu\text{m}$  cellulose acetate membranes prior to analysis. Samples were analyzed at 253.7 nm using a UV-vis spectrometer (Perkin-Elmer, Model Lambda 25 UV-vis spectrometer) with matched quartz cells providing a light path of 1 cm. Potassium hydrogen biphthalate (KHP) was used to check the precision of the spectrophotometer.

Table 1  
The experimental jar-test conditions

Coagulant	Coagulant dosage (mg/L)	pH adjustment
Alum ( $\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$ )	0, 10, 20, 40, 60, 80	Uncontrolled pH and controlled pH at 6.5, 6 and 5.5
Ferric chloride ( $\text{FeCl}_3$ )	0, 10, 20, 40, 60, 80	Uncontrolled pH and controlled pH at 6, 5.5 and 5

TOC and DOC were analyzed in accordance with *Standard Methods* 5310 (total organic carbon) and section 5310 D, (wet-oxidation method) [19]. Water samples were filtered through glass-fiber filters (GFC) of nominal pore size ( $1.2 \mu\text{m}$ ) prior to analyzing TOC. Water samples were filtered through a prewashed  $0.45 \mu\text{m}$  cellulose acetate membrane prior to analyzing DOC. A TOC Analyzer (O.I. analytical 1010) was used to measure both TOC and DOC. The analyzer was regularly calibrated using KHP.

Three analytical methods for THM analyses, using bromofluorobenzene standard solution as the internal standard, were used to analyze THMs, as briefly described below:

- THMs were measured in accordance with *Standard Methods* 5710. (Formation of trihalomethanes and other disinfection by-products) [19]. A chlorine demand test was also included in this method. Free chlorine residual of chlorinated samples after 1 and 7 days ranged from 3 to 5 mg/L. Only coagulated water samples (except raw water) were filtered through the GFC prior to analyzing chlorine demand.
- Free chlorine residual was measured in accordance with *Standard Methods* 4500-ClG. (DPD colorimetric method) [19].
- Liquid–liquid extraction; water samples were extracted in accordance with *Standard Methods* 6232B. (Liquid–liquid extraction gas chromatography method) [19]. Water samples were filtered through GFC filters prior to analyzing for THMs (raw water excepted). Agilent gas chromatography (6890 series) with micro electron capture detector ( $\mu\text{ECD}$ ), auto sampler and chromatographic column (J&W Science DB-624),  $0.2 \text{ mm} \times 25 \text{ m}$   $1.12 \mu\text{m}$  film were used to analyze  $\text{TTHM}_0$  (initial) and  $\text{TTHM}_7$  (at 7-days).

Table 2  
Water sample and analytical parameters

Parameter	Raw water	Coagulated water after jar-test experiment	Coagulated water after jar-test experiment and 7-day holding
Turbidity (NTU)	✓	✓	–
UV-254 (1/cm)	✓ <sup>a</sup>	✓ <sup>a</sup>	–
TOC (mg/L)	✓	✓ <sup>b</sup>	–
DOC (mg/L)	✓ <sup>a</sup>	✓ <sup>a</sup>	–
SUVA (L/mg-m)	✓ <sup>a</sup>	✓ <sup>a</sup>	–
Chlorine demand (mg/L)	✓	✓ <sup>b</sup>	✓
Free chlorine residual (mg/L)	✓	–	✓ <sup>b</sup>
$\text{TTHM}_0$ ( $\mu\text{g/L}$ )	✓	✓ <sup>b</sup>	–
$\text{TTHM}_7$ ( $\mu\text{g/L}$ )	✓	–	✓ <sup>b</sup>

$\text{TTHMFP} = \text{TTHM}_7 - \text{TTHM}_0$ .

<sup>a</sup> Filtered samples by using  $0.45 \mu\text{m}$  cellulose acetate membrane.

<sup>b</sup> Filtered samples by using  $1.2 \mu\text{m}$  GFC.

### 2.3. Experimental procedure

#### 2.3.1. Jar-test apparatus and process

Using a multistage stirrer apparatus, simultaneous tests were conducted on a series of samples covering a range of coagulant concentration. On the addition of the coagulants, which consisted of regular-grade alum ( $\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$ ) and analytical-grade ferric chloride ( $\text{FeCl}_3$ ), the samples were rapidly mixed at 100 rpm for 1 min, followed by slow mixing at 30 rpm for 30 min. The samples were then allowed to stand for 1 h for settlement [15]. After this period the turbidity of the supernatant and UV-254, TOC, DOC, SUVA and THMFP of the filtered supernatant were measured and the lowest coagulant dose giving adequate removal was noted. Using the same concentration of coagulant, a second similar set of tests were also performed on pH-adjusted samples so as to determine the optimum pH values for such coagulation. The jar-test procedure, as stated previously, was conducted under the conditions of coagulation as depicted in Table 1.

#### 2.4. Water sample and analytical parameters

Treated industrial estate wastewater and coagulated water were collected as samples for analysis in this study. The coagulated water was identified as reclaimed water in this study. The water samples and analytical parameters performed during the experiments are presented in Table 2 and Fig. 1.

## 3. Results and discussions

### 3.1. Characteristics of treated industrial estate wastewater

In this study, the characteristics of treated industrial estate wastewater over a five-month period between October 2002

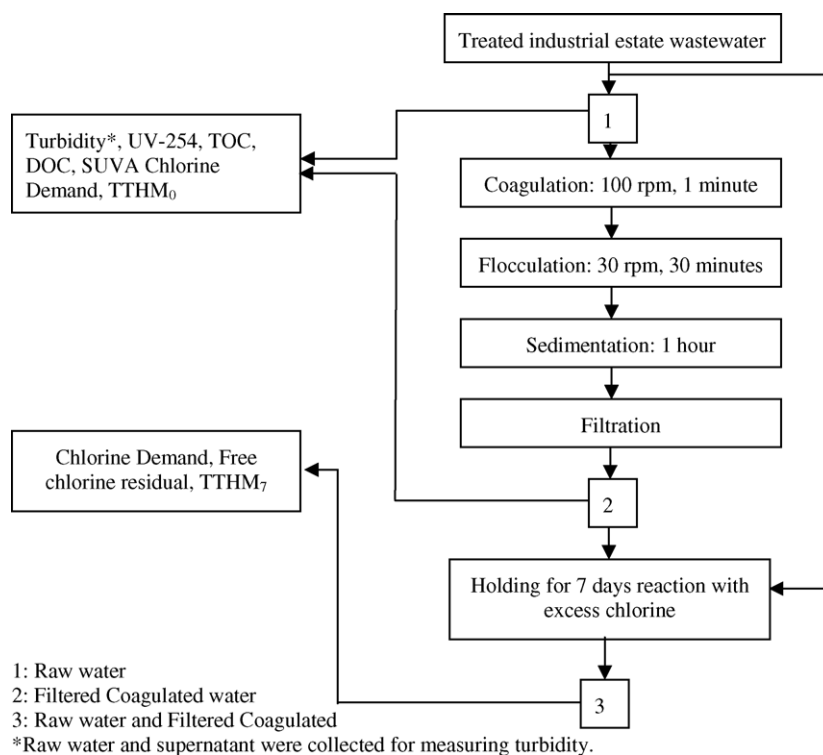


Fig. 1. Water sample and analytical parameters.

and February 2003 are summarized in Table 3. These indicate a similarity to both municipal reclaimed wastewater and typical surface waters in Thailand.

### 3.2. Turbidity removal by alum and ferric chloride coagulation

Raw water turbidity, TOC, DOC and SUVA values at the beginning of each experiment were slightly different because raw water samples were separately collected for conducting the coagulation. It was due to the recommendation from the standard method [19] that water samples should be measured for THMFP within 14 days. Regarding this limited, one-time sampling coagulation could be only performed at one pH with a variation of alum and ferric chloride from 0 to 80 mg/L.

Table 3  
Characteristics of treated industrial estate wastewater

Parameters	Range of values	Average values
pH	6.8–7.7	7.2
Turbidity (NTU)	10.8–30.9	17.7
Alkalinity (mg/L as CaCO <sub>3</sub> /L)	53.4–116.4	86.4
Temperature (°C)	22.0–24.6	24.2
UV absorbance at 254 nm.(cm <sup>-1</sup> )	0.1527–0.3024	0.2221
TOC (mg/L) <sup>a</sup>	5.18–7.29	6.13
DOC (mg/L) <sup>a</sup>	4.52–5.92	5.14
SUVA (L/mg-m) <sup>a</sup>	3.63–6.68	4.73
TTHM <sub>0</sub> (µg/L)	0–14.8	8.006

<sup>a</sup> TOC, DOC and SUVA were done only in the last two months of the study.

As shown in Figs. 2 and 3, alum and ferric chloride dosages of 10 mg/L at uncontrolled pH could promptly remove turbidity in the supernatant by approximately 85%. In comparison maximum turbidity removal in the supernatant was approximately 97% at alum and ferric chloride dosages of up to 80 mg/L at uncontrolled pH. These results indicate that alum and ferric chloride coagulation at uncontrolled pH could produce very clear reclaimed water from treated industrial estate wastewater and even better results could be obtained at controlled pH. However, when industrial use of water is the main target outcome, the removal of TOC, DOC and SUVA are important. There is therefore, a need to conduct further study on the removal of TOC, DOC SUVA in order to gain suitable coagulation conditions for the removal of turbidity, TOC, DOC and SUVA.

### 3.3. TOC and DOC removal by alum and ferric chloride coagulation and filtration

In this study, TOC and DOC data are presented in Figs. 4–7. TOC was gradually reduced from the average value of about 6.12 mg/L to approximately 4.0 mg/L by alum and ferric chloride dosages of approximately 40 mg/L, a reduction of about 35%. Moreover, DOC was reduced from the average value of more or less 5.14 mg/L to a level of about 4.0 mg/L (approximately 23% reduction), by alum and ferric chloride dosages of about 40 mg/L.

Additionally, the optimal pH for TOC and DOC removal were 5.5 and 5 for alum and ferric chloride coagulation,

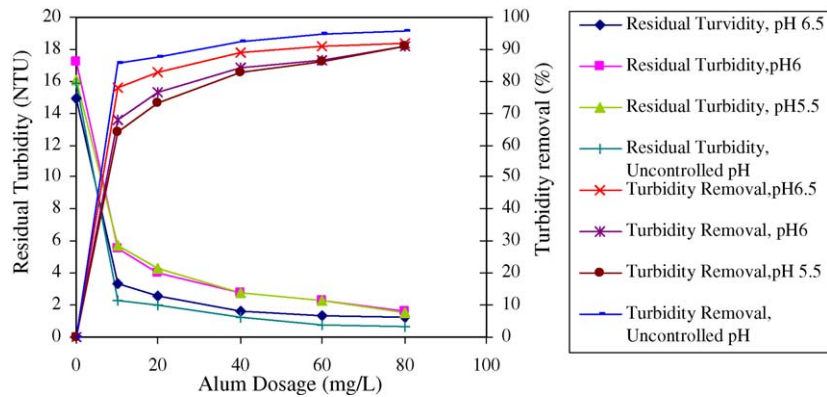


Fig. 2. Residual turbidity and percent removal of turbidity in supernatant as a function of alum dosage at uncontrolled pH and variation controlled pH.

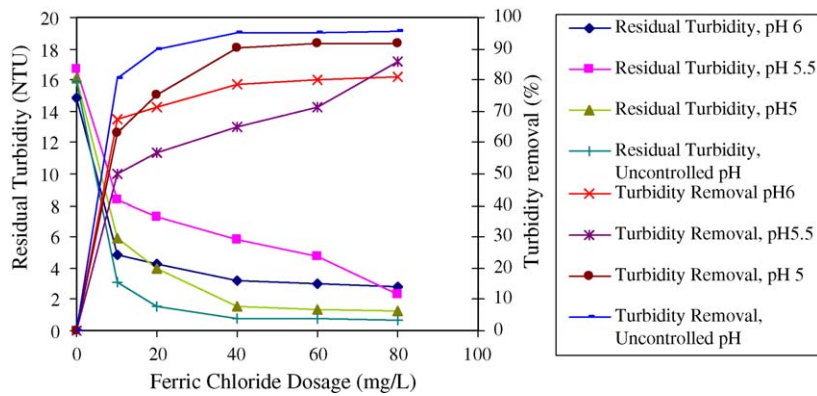


Fig. 3. Residual turbidity and percent removal of turbidity in supernatant as a function of ferric chloride dosage at uncontrolled pH and variation controlled pH.

respectively. The optimal dosage for TOC and DOC removal by alum and ferric chloride coagulation were 40 mg/L for both. An increase in dosage above 40 mg/L resulted in a slight increase in DOC and TOC removal. However, ferric chloride is more effective than alum in removing TOC and DOC because at a dosage of 40 mg/L and a controlled pH of 5 ferric chloride removed approximately 45 and 40% of TOC and DOC, respectively, whereas at a dosage of 40 mg/L and a controlled pH of 5.5 alum removed approximately 30% of both TOC and DOC. Nevertheless, in comparison with TOC

and DOC reduction results from the literature, results in this study demonstrated a slightly low TOC and DOC reduction.

### 3.4. Effects of alum and ferric chloride coagulation-filtration on SUVA

As shown in Figs. 8 and 9, SUVA was reduced (by approximately 60%) to close to 2 L/mg-m (a recommended value by [15]) by 20 mg/L alum and ferric chloride at all controlled pH values. Based on SUVA results and literature reviews, it

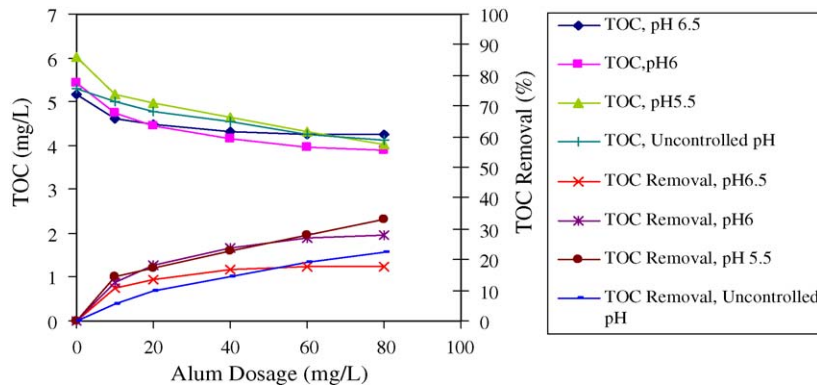


Fig. 4. TOC and percentage TOC removal as a function of alum dosage at controlled and uncontrolled pH.



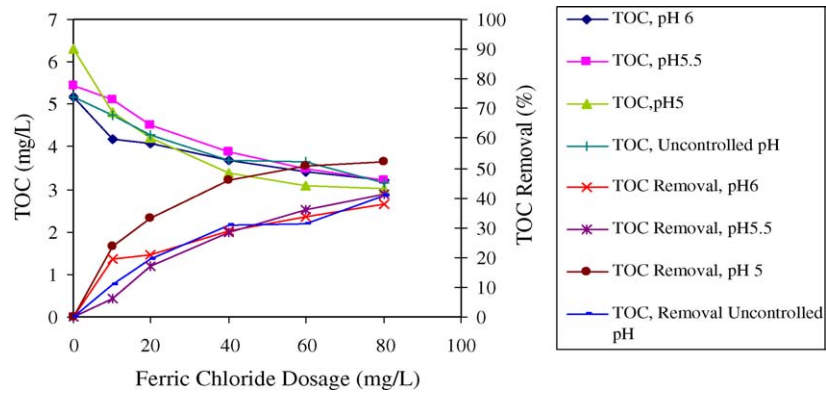


Fig. 5. TOC and percentage TOC removal as a function of ferric chloride dosage at controlled and uncontrolled pH.

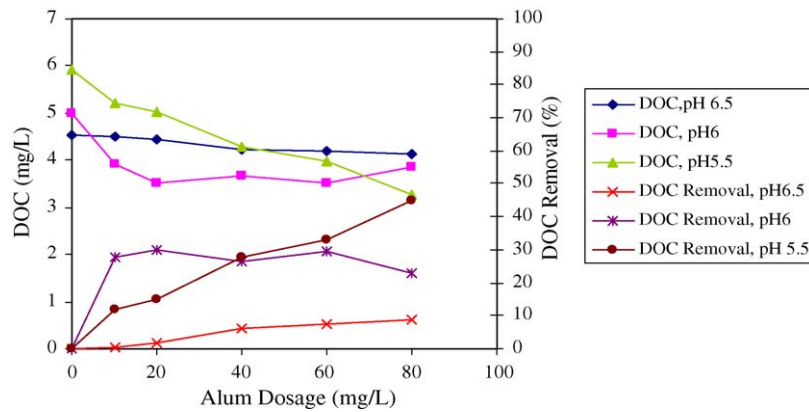


Fig. 6. DOC and percentage of DOC removal as a function of alum dosage at controlled pH.

can be stated that alum and ferric chloride dosages of about 20 mg/L should remove most humic acids in water. Incremental alum and ferric chloride dosages can only remove a small amount of fulvic acids, which resulted in constant SUVA values in coagulated water.

Interestingly, the removal of SUVA (by approximately 80%) by alum and ferric chloride coagulation is more effective than the removal of DOC (approximately 35%). It can be concluded from these results that bigger aromatic molecules

are removed more effectively than both smaller aromatic molecules and linear molecular matter.

### 3.5. Effects of alum and ferric chlorine coagulation-filtration on chlorine demand at optimal pH

Table 4 shows the chlorine demand after 1 and 7-days reaction in raw and filtered supernatant after coagulation (coagulated water). The chlorine demand in coagulated water

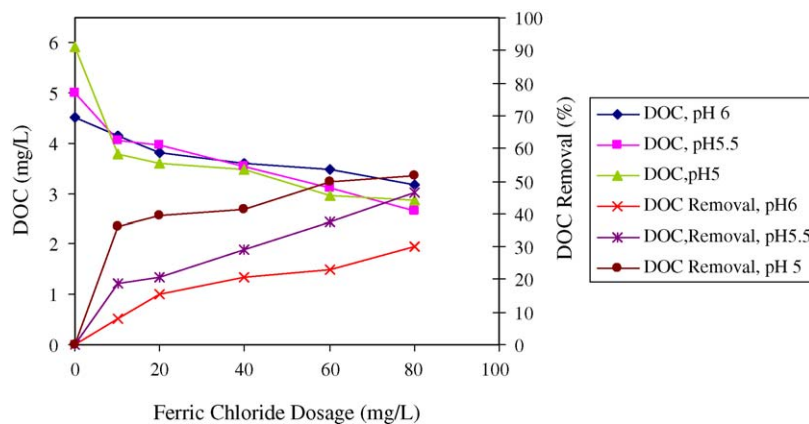


Fig. 7. DOC and percentage of DOC removal as a function of ferric chloride dosage at controlled pH.

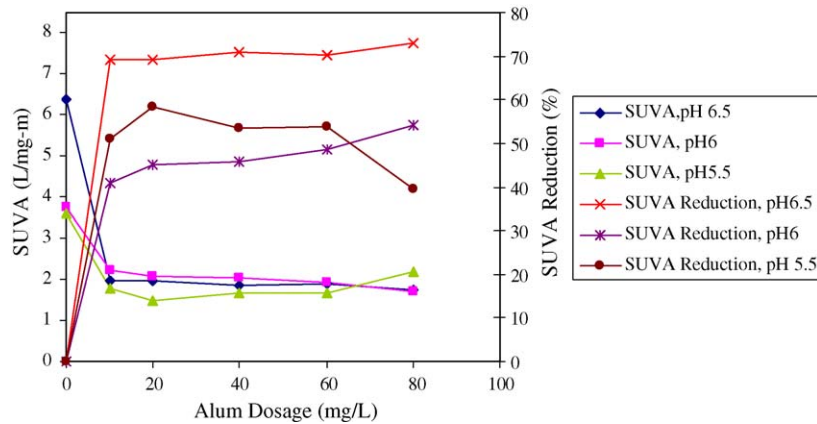


Fig. 8. SUVA and percentage of SUVA reduction as a function of alum dosage at controlled pH.

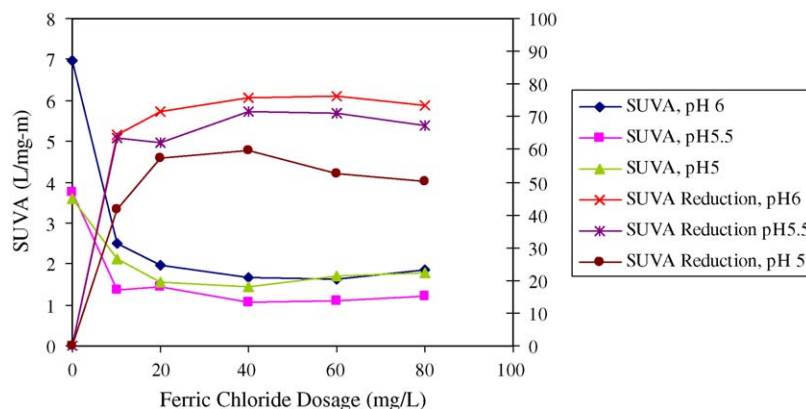


Fig. 9. SUVA and percentage of SUVA reduction as a function of ferric chloride dosage at controlled pH.

at 1-day reaction was the same as that at 7-days reaction. In contrast, chlorine demand in raw water at 1-day reaction was significantly different to those at 7-days reaction. Thus, it can be pointed out that raw water (treated industrial estate wastewater) utilized longer reaction time with chlorine than that of coagulated water. Interestingly, with reference to [7], it has been recognized that correlation levels were divided into four categories:  $R^2 > 0.9$  was considered a good correlation,  $0.7 < R^2 < 0.9$  a moderate correlation,  $0.5 < R^2 < 0.7$  a fair cor-

relation and  $R^2 < 0.5$  a poor correlation. For poor correlation ( $R^2 < 0.5$ ), regression analysis was not performed and hence the slope and intercept for the equation were not acceptable. By using the data from Table 3, it is also noteworthy that the good correlation coefficient of 0.9791 ( $n = 10$ ) was obtained for the relationship between chlorine demand at 1-day reaction and chlorine demand at 7-days reaction (correlation was significant at the 0.01 level). The following equation could be used to express such correlation: Chlorine demand after 7-days reaction = 0.9212 (chlorine demand after 1-day reaction) + 4.9212.

Table 4  
Chlorine demand at 1- and 7-day reaction of raw and coagulated water

Sample type	Chlorine demand at 1-day reaction	Chlorine demand at 7-days reaction
Raw water	119.6	142.6
Raw water	118.5	142.1
Alum 10 mg/L	88.8	89.8
Alum 20 mg/L	87.8	88.5
Alum 40 mg/L	92.6	92.8
Alum 60 mg/L	95.6	95.9
Alum 80 mg/L	94.5	94.4
FeCl <sub>3</sub> 10 mg/L	84.0	83.7
FeCl <sub>3</sub> 20 mg/L	84.5	85.4
FeCl <sub>3</sub> 80 mg/L	83.9	85.2

### 3.6. THMFP species and its reduction at optimal pH coagulation

#### 3.6.1. Coagulation by alum at the optimal pH of 5.5

Based on the THMFP species data in raw water and in coagulated water by alum is shown in Fig. 10 and Table 5. It was observed that chloroform in raw water and coagulated water made up about 65 and 60% of total THMFP, respectively. Dichlorobromoform, dibromochloroform, and bromoform were also found in raw water and in coagulated water. The percentages of these species in raw water were approximately 20, 10 and 5%, respectively.

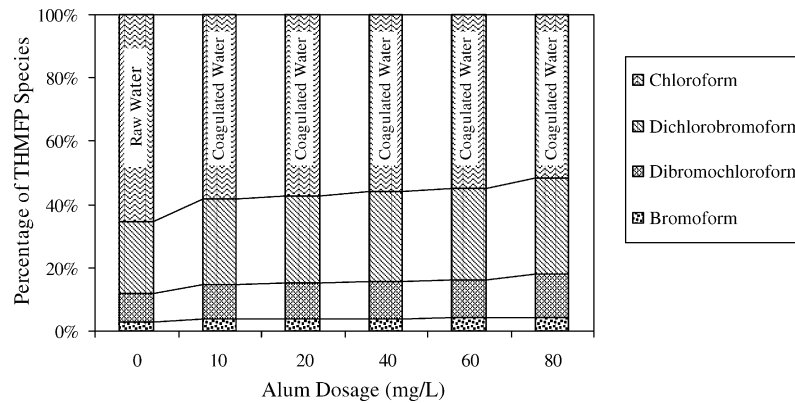


Fig. 10. THMFP species in raw and coagulated water with various alum dosages at the optimal pH of 5.5.

However, at nearly all alum dosages, dichlorobromoform, dibromochloroform, and bromoform in coagulated water made up approximately 25, 10 and 5% of total THMFP, respectively. It is noted that chloroform was the predominant THMFP species in treated industrial estate wastewater and reclaimed water while dichlorobromoform, dibromochloroform, and bromoform were found in minority.

Concentrations in terms of  $\mu\text{g/L}$  of each of the THMFP species in raw water and in coagulated water are also tabulated in Table 5. It can be seen in Table 5 that chloroform, dichlorobromoform, dibromochloroform, and bromoform were found in treated industrial estate wastewater at 313.26, 109.44, 43.58 and 14.39  $\mu\text{g/L}$ , respectively, with total a THMFP of 480.68  $\mu\text{g/L}$ . In addition, it was also noticed that the best alum coagulation condition for total THMFP removal in this study was at the alum dosage of 80 mg/L at pH 5.5 by which total THMFP could only be reduced from 480.68 to 359.39  $\mu\text{g/L}$ . Concerning the reduction of THMFP species by alum coagulation at the optimal pH of 5.5 as depicted in Table 5, a chloroform removal efficiency by alum coagulation of 40.82% was observed while other species could not be efficiently removed. However, it can be stated that a total THMFP of 25.23% could be removed by coagulation at an alum dosage of about 80 mg/L at pH 5.5.

### 3.6.2. Coagulation by ferric chloride at the optimal pH of 5

As shown in Fig. 11 and Table 6, chloroform in raw water and coagulated water made up approximately 60 and 55% of

total THMFP, respectively. In other words, dichlorobromoform, dibromochloroform, and bromoform were also found in the raw and coagulated water. The percentage of total THMFP made up by dichlorobromoform, dibromochloroform, and bromoform in raw water was approximately 20, 15 and 5%, respectively, while in coagulated water they made up approximately 25, 15 and 5%, respectively. Again, chloroform was the dominant THMFP species in treated industrial estate wastewater and in reclaimed water while dichlorobromoform, dibromochloroform and bromoform were found in minority. The concentrations in terms of  $\mu\text{g/L}$  of each THMFP species in raw and coagulated water are also demonstrated in Table 6. It shows that chloroform, dichlorobromoform, dibromochloroform and bromoform were found in treated industrial estate wastewater at 284.23, 123.11, 65.54 and 18.92  $\mu\text{g/L}$ , respectively, with total THMFP at 491.80  $\mu\text{g/L}$ .

In addition, it was also noticed that the best ferric chloride coagulation condition for total THMFP removal in this study was at a dosage of 80 mg/L at pH 5 by which total THMFP could only be lowered from 491.80 to 355.54  $\mu\text{g/L}$ . With respect to coagulation by ferric chloride, the removal efficiency of chloroform, dichlorobromoform, dibromochloroform and bromoform at pH 5 and an 80 mg/L dosage were 31.03, 15.29, 38.72 and 20.45%, respectively. As a result, total THMFP removal by 27.71% was attained in this study.

Regarding the performance of ferric chloride coagulation in comparison with that of alum coagulation, as described

Table 5

THMFP species and percentage reduction of THMFP species in raw and coagulated water at the optimal controlled pH of 5.5 and with various alum dosages

THMFP species	Raw water	Coagulated water					Percent reduction (%)				
		Alum dosages (mg/L)					Alum dosages (mg/L)				
		10	20	40	60	80	10	20	40	60	80
$\text{CHCl}_3$ ( $\mu\text{g/L}$ )	313.26	239.34	224.95	221.32	207.3	185.36	23.6	28.2	29.3	33.8	40.8
$\text{CHCl}_2\text{Br}$ ( $\mu\text{g/L}$ )	109.44	110.55	108.23	113.24	109.83	109.25	0 (–)	0 (–)	0 (–)	0 (–)	0.17
$\text{CHClBr}_2$ ( $\mu\text{g/L}$ )	43.58	44.41	44.00	45.89	45.34	48.72	0 (–)	0 (–)	0 (–)	0 (–)	0 (–)
$\text{CHBr}_3$ ( $\mu\text{g/L}$ )	14.39	14.99	15.00	15.39	15.35	16.05	0 (–)	0 (–)	0 (–)	0 (–)	0 (–)
Total ( $\mu\text{g/L}$ )	480.68	409.37	392.19	395.88	377.85	359.39	14.8	18.4	17.7	21.4	25.2



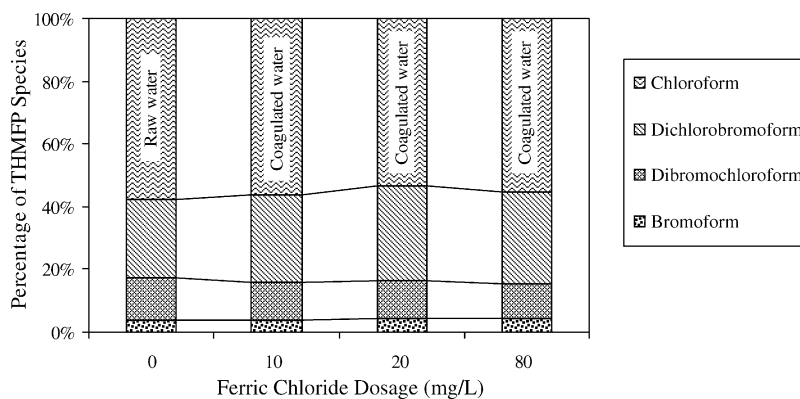


Fig. 11. THMFP species in raw and coagulated water with various ferric chloride dosages at optimal pH of 5.

Table 6

THMFP species and percent reduction of THMFP species in raw and coagulated water with various ferric chloride dosages at optimal controlled pH of 5

THMFP species	Raw water	Coagulated water			Percent reduction (%)		
		Ferric chloride dosages (mg/L)			Ferric chloride dosages (mg/L)		
		10	20	80	10	20	80
CHCl <sub>3</sub> (μg/L)	284.23	213.99	195.16	196.04	24.7	31.3	31.0
CHCl <sub>2</sub> Br (μg/L)	123.11	108.12	109.56	104.28	12.12	11.0	15.3
CHClBr <sub>2</sub> (μg/L)	65.54	44.64	44.70	40.16	31.9	31.9	38.7
CHBr <sub>3</sub> (μg/L)	18.92	15.30	15.44	15.05	19.1	18.4	20.5
Total (μg/L)	491.80	382.06	364.88	355.54	22.3	25.8	27.7

earlier, it could be implied that total THMFP reduction efficiencies by ferric chloride and alum coagulation were comparable, by 27.71 and 25.23%, respectively. However, alum coagulation could only remove chloroform and was not able to remove dichlorobromoform, dibromochloroform and bromoform efficiently, and this is contrary to the results of ferric chloride coagulation. Hence, ferric chloride is more effective than alum in reducing THMFP. Finally, approximately 28 and 25% of THMFP was reduced by ferric chloride alum and coagulation, respectively while SUVA was reduced by approximately 80%. These results suggest that as stated previously, bigger aromatic molecules are removed more effectively than both smaller aromatic molecules and linear molecular matter, where SUVA represented the aromatic molecules. Therefore, an 80% reduction of SUVA represented the removal of big aromatic molecules while the remaining 20% consisted of small aromatic molecules and linear molecular matter that may easily react with chlorine to form THMFP.

#### 4. Conclusions

The aim of this work was to remove organic matter and THMFP from reclaimed water from treated industrial estate wastewater using alum and ferric chloride coagulation. The optimal pH for TOC and DOC removal were 5.5 and 5 for alum and ferric chloride coagulation, respectively. The optimal dosage for TOC and DOC removal by alum and

ferric chloride coagulation were both 40 mg/L. Alum and ferric chloride dosages of about 20 mg/L effectively removed approximately 80% of SUVA. Chlorine demands at 1-day reaction were the same as those at 7-day reaction with a correlation coefficient of 0.98 ( $n = 10$ , correlation was significant at the 0.01 level). The resulting expression was as follows: Chlorine demand after 7-days reaction = 0.9212 (chlorine demand after 1-day reaction) + 4.9212. In terms of THMFP species, chloroform at approximately 65 and 60% of total THMFP was found as the predominant THMFP species in treated industrial estate wastewater and in reclaimed water, respectively in comparison with the bromoform, dichlorobromoform and dibromochloroform species. Total THMFP reduction efficiencies by ferric chloride and alum coagulation were comparable at 28 and 25%, respectively. Finally, it was shown that ferric chloride is more effective than alum in reducing TOC, DOC, SUVA and THMFP. In addition, more research is needed in further optimizing the removal of THM precursors in treated wastewaters by various coagulants and coagulant aids in areas where water resources are scarce and where there is a growing need for water reuse.

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