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Water blending effects on coagulation-flocculation using aluminum sulfate (alum), polyaluminum chloride (PAC), and ferric chloride ($FeCl_3$) using multiple water sources

Hanbai Park[a,*], Sung-il Lim[a], Hosun Lee[b], Dal-Sik Woo[a]

[a]*Water and Environmental Science Department, Korea Interfacial Science & Engineering Institute, 400-18 Nambu-daero, Dongnam-gu, Cheonan-si 330-270, Korea, Tel. +82 41 522 5025; Fax: +82 41 588 9612; email: parkhanbai@gmail.com (H. Park)*
[b]*Smart Water Grid Research Group, Incheon National University, 7-46 Songdo-dong, Yeonsu-gu, Incheon-si, Korea*

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ABSTRACT

This study investigated three common coagulants (alum sulfate (alum), polyaluminum chloride (PAC), and ferric chloride ($FeCl_3$)) to determine the best coagulant and optimal dosages in terms of TOC, DOC, turbidity, and conductivity in multiple types of blended water. In the blended surface water and ground water experiment, PAC displayed the best performance in terms of coagulation at a dosage of 20 mg/L. In the blending treated sewage water and rainwater experiment, the removal efficiency of TOC, DOC, and turbidity was the highest for PAC at a dosage of 20 mg/L. In the seawater, brackish water, and rainwater blending experiment, the turbidity, TOC, and DOC were efficiently removed at a PAC dosage of 20–30 mg/L. The coagulant effects on blending water samples displayed a higher removal efficiency that increased with the blending ratio. The outcomes from these experiments can be used in future water treatment processes that use multiple resources.

Keywords: Coagulation; TOC; DOC; Turbidity removal; Multiple water source blending

1. Introduction

The rapid increase in water demand due to urbanization, population growth, and global climate change has resulted in a global water deficiency. The use of multiple water resources is one desirable solution for overcoming this problem, though information about multiple water use and related water treatment technologies is quite limited, as few studies currently exist. Coagulation is a common process for removing suspended and dissolved solids in water treatment operations [1]. Untreated water primarily contains suspended and dissolved colloids that are dependent on water qualities; these colloids affect the degree of water stability and quality. However, the effectiveness of coagulation has a complex dependency upon the nature of the raw water quality, including TOC, DOC, pH, alkalinity, turbidity, and conductivity and the type of coagulants used.

Widely used coagulants include aluminum sulfate (alum), polyaluminum chloride (PAC), and ferric chloride ($FeCl_3$) [2]. Their efficacies depend on the physical and chemical characteristics of the raw water and the operating conditions [3], though among these

*Corresponding author.

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inorganic coagulants, iron salts are often more efficient than aluminum salts [4]. In recent years, there has also been a rising interest in the use of polymerized forms of metal coagulants, such as PAC, for water treatments in Europe, Japan, and North America due to their economic benefits and potential for wider use [5,6]. Alum is a standard chemical in coagulation and flocculation processes, as it effectively attracts inorganic suspended solids [7]. Due to its poor efficiency for attracting organic suspended solids, a large alum dosage is typically required based on the water quality. $FeCl_3$ is known as an alternative to alum, as it can efficiently remove inorganic suspended solids and provides more compact sludge than alum [8]. As a final compound, however, PAC is claimed to be advantageous over conventional coagulants because of its high particulate and/or organic matter removal efficiency, in addition to its natural advantages of lower alkalinity consumption and lesser sludge production [6]. The coagulants (alum and PAC) with a cationic polyacrylamide (C-PAM) in removing chemical oxygen demand (COD) and turbidity using paper-recycling wastewater was investigated and they found that 40 mg/L PAC dosage and 4.5 mg/L C-PAM dosage at pH 4.5 provided 92% reduction of turbidity, 97% removal of COD and SVI (Slit volume index) 80 mL/g [9]. PAC (12%Al) shows superior coagulation performance than PAC-18 (9% Al), when applied for the treatment of contaminated natural water, or for real wastewater (biologically pre-treated leachate) samples [10]. This experiment investigated the effects of coagulation for various ratios of blended water obtained from multiple water resources. In this study, three common coagulants (alum, PAC, and $FeCl_3$) were investigated in order to determine optimal coagulant dosages in terms of TOC, DOC, turbidity, and conductivity in multiple types of blended water. Optimal coagulant dosages are a critical factor for floc formation and coagulation effectiveness, and the adequate control of coagulants can deliver better performance with the cost-effectiveness in water treatment plants. The cost-effectiveness is a very important parameter, which designates the ability of a product to be produced for commercial purposes [10]. The results from this experiment were applied to the pilot plant experiment in Bupyung, Incheon, South Korea shown in Fig. 1. This process was designed to achieve the appropriate water quality parameters using surface water, groundwater, treated sewage water, rain water, seawater, and brackish water by blending. Water quality parameters were estimated in terms of TOC, DOC, turbidity, and pH, which can be measured by automatic gauges.

2. Materials and methods

2.1. Materials

Multiple water resource characteristics and their intake areas are shown in Table 1. Two of the coagulants used, aluminum sulfate (8%) and PAC (17%), were purchased from Eyoung Chemical (South Korea); $FeCl_3$ (42%) was purchased from Chang Woo Co., Ltd (South Korea).

2.2. Jar test

Because of the complexity of using multiple water resources, a jar test should be used as a pilot-scale experiment. A conventional jar test apparatus was used in the experiments to coagulate various blended water resources using alum, $FeCl_3$, and PAC. The batch test was conducted, comprised of a series of six 1,000 mL beakers with six-spindle steel paddles. The six beakers containing 500 mL of blended water were rapidly stirred at 150 rpm for 1 min, as the desired doses of the three coagulants were simultaneously added; the samples were then slow mixed at 50 rpm for 20 min. After agitation, the suspensions were allowed to settle for 30 min, and samples were collected using a pipette to measure the conductivity, turbidity, pH, TOC, and DOC for comparison with the initial concentrations. All tests were performed at ambient temperatures in the range of 20–28˚C. The study was conducted by varying a few experimental parameters, which included PAC dosage (10–50 mg/L) and pH (3.4.9–7.6), to study the effectiveness of coagulation and the optimum parameters for each condition.

2.3. Analysis

TOC was analyzed using the wet chemical oxidation method [11]. This method is used to measure the oxygen demand for the oxidation of organic matters by using a strong chemical oxidant that is equivalent to the amount of organic matter in the sample. DOC was measured using a CA Syringe filter (25 mm/0.45 μm) and analyzed using a Shimadzu V-series analyzer (Japan). Moreover, the turbidity was measured using Hach Model DR/2100 spectrophotometer (USA), and the water pH was measured using a Hanna pH meter (USA). The removal efficiency (percent removal) was calculated using the following formula:

$$\text{Removal}(\%) = \frac{C_0 - C}{C_0} \times 100 \quad (1)$$

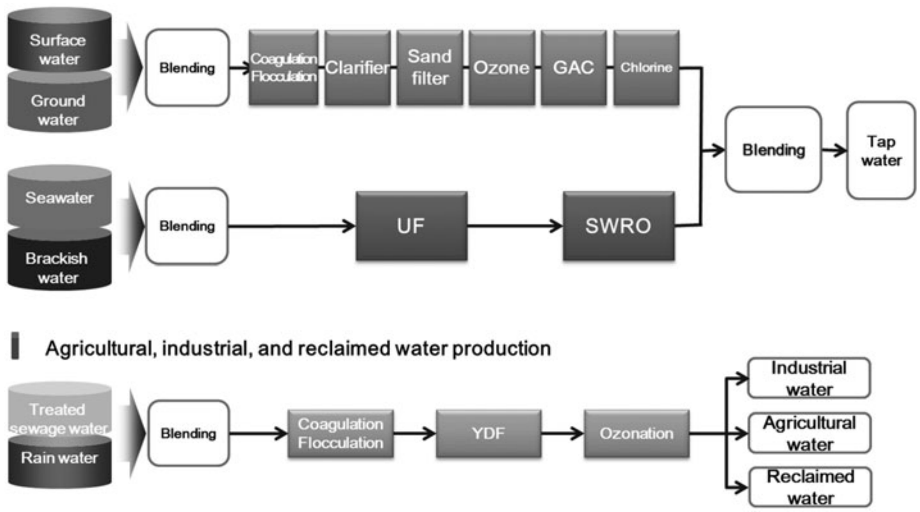

Fig. 1. A schematic diagram of the pilot plant in Bupyung, Incheon, South Korea.

Table 1
Characteristics of used water samples

	Analysis type					
Water type	Temperature (℃)	pH	Turbidity (NTU)	TOC (mg/L)	DOC (mg/L)	Water intake area
Surface water	18	7.56	3.87	1.625	1.258	Pungnap intake Seoul, Korea
Ground water	18	7.49	1	0.325	0.269	Cheongdang-dong Cheonan, Korea
Treated sewage water	20	7.42	9.82	7.572	4.848	Environmental center Cheonan, Korea
Sea water	20	8.09	3.87	1.378	1.088	Offshore Incheon, Korea
Rainwater	20	7.82	5.12	6.899	6.609	Cheongdang-dong Cheonan, Korea
Brackish water	20	7.41	6.75	3.627	3.337	Gonchon Brook Incheon, Korea

where C_0 is the initial concentration of DOC, TOC, and turbidity, and C is the concentration after coagulation.

3. Results and discussion

3.1. Coagulation effect on water blended using surface water and groundwater

This study evaluated the coagulation effects on blended water created using surface water and groundwater, blended at ratios of 9:1, 8:2, 7:3, 6:4, and 5:5. The blending ratios were decided based on the pilot plant experiment scenarios. The three coagulants, alum, PAC, and $FeCl_3$, were added at concentration ranges of 10–50 mg/L for each blended water sample. Table 2 displays the characteristics of surface and ground water blended samples at different ratios.

In Fig. 2, characteristics of used raw water provided different qualities by blending ground water ratio. Turbidity, TOC, and DOC decreased by increasing ground water ratio. Among these, turbidity responded the highest effect on changing blending ground water ratio. For coagulation, different water qualities were a key factor for different amounts of dosage [12].

Fig. 3 exhibited coagulation effects on TOC, DOC, and turbidity using PAC, alum, $FeCl_3$ in different ratios of surface water and ground water. For PAC removal, the optimal dosage was selected to be 30 mg/L based on the TOC, DOC, and turbidity removal analytical results. The TOC removal efficiencies for the different surface water and ground water blending ratios at a 30 mg/L PAC dose were 41% (9:1), 26% (8:2), 31% (7:3), 29% (6:4), and 30% (5:5). The DOC removal efficiencies were 55% (9:1), 83% (8:2), 64% (7:3), 60% (6:4), and 81% (5:5), and turbidity

Table 2
Characteristics of water samples with different blended ratios

Blending proportion Surface water: ground water	Analysis data					
	Temperature (˚C)	pH	Conductivity (μS/cm)	Turbidity (NTU)	TOC (mg/L)	DOC (mg/L)
9.5:0.5	18	7.45	0.2	3.54	1.459	1.096
9:1	18	7.35	0.2	3.18	1.110	1.021
8.5:1.5	18	7.35	0.2	2.89	1.093	0.918
8:2	18	7.61	0.2	2.71	0.880	0.983
7.5:2.5	18	7.60	0.2	2.37	0.571	0.541

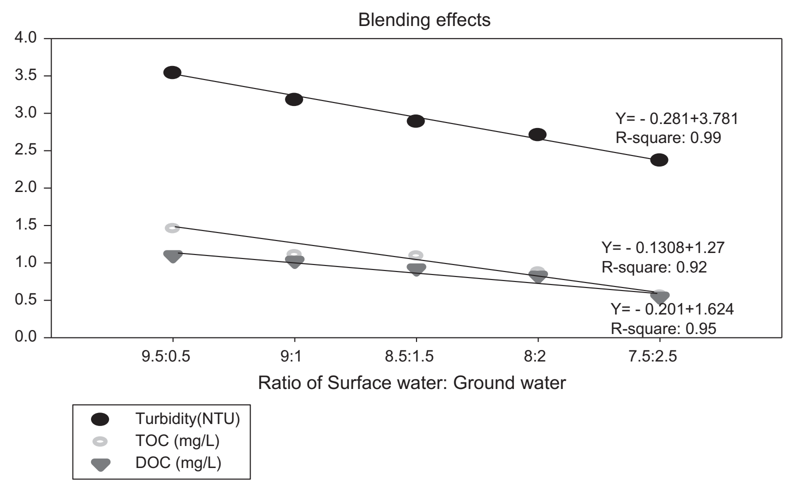

Fig. 2. Blending effects on turbidity, TOC, DOC parameters using surface water and ground water.

removal efficiencies were 44% (9:1), 40% (8:2), 43% (7:3), 45% (6:4), and 43% (5:5).

According to the alum evaluation, the optimal dosage was evaluated at 30 mg/L by analyzing the TOC, DOC, and turbidity removal results. The TOC removal was 37% (9:1), 20% (8:2), 24% (7:3), 26% (6:4), and 25% (5:5). The DOC removal was 37% (9:1), 58% (8:2), 67% (7:3), 65% (6:4), and 79% (5:5), and the turbidity removal was 13% (9:1), 15% (8:2), 16% (7:3), 23% (6:4), and 16% (5:5).

The optimal dosage of $FeCl_3$ was found at 30 mg/L. The TOC removal was 28% (9:1), 17% (8:2), 24% (7:3), 23% (6:4), and 19% (5:5). The DOC removal was estimated to be 24% (9:1), 31% (8:2), 39% (7:3), 41% (6:4), and 44% (5:5), and the turbidity removal was 13% (9:1), 15% (8:2), 16% (7:3), 23% (6:4), and 15% (5:5).

In general, the PAC, alum, and $FeCl_3$ tended to display a higher removal efficiency at increasing blending ratios of ground water. Among these, PAC displayed the highest TOC, DOC, and turbidity removal efficiency at the optimal dosage of 20 mg/L.

3.2. Coagulation effects on blended water comprised of treated sewage water and rainwater

This experiment was conducted to determine the optimal concentrations of alum, FeO_3, and PAC at blending ratios of treated sewage water and rainwater of 9.5:0.5, 9:1, 8.5:1.5, 8:2, and 7.5:2.5. The blending ratios were determined to produce the best types of waters such as industrial, agricultural, and reclaimed water in the pilot plant (Fig. 1). While the intended target for this experiment was to use a lower concentration of coagulants and to deliver the best efficiency, coagulant concentrations in the range of 10–50 mg/L were used at a temperature of 20˚C. The characteristics of water samples with different blended ratios are displayed in Table 3.

In Fig. 4, blending effects on turbidity, TOC, DOC parameters using treated sewage water and rain water were shown. Turbidity, TOC, and DOC decreased linearly by increasing rain water proportion. Thus, more rain water blending could decrease turbidity, TOC, and DOC concentrations.

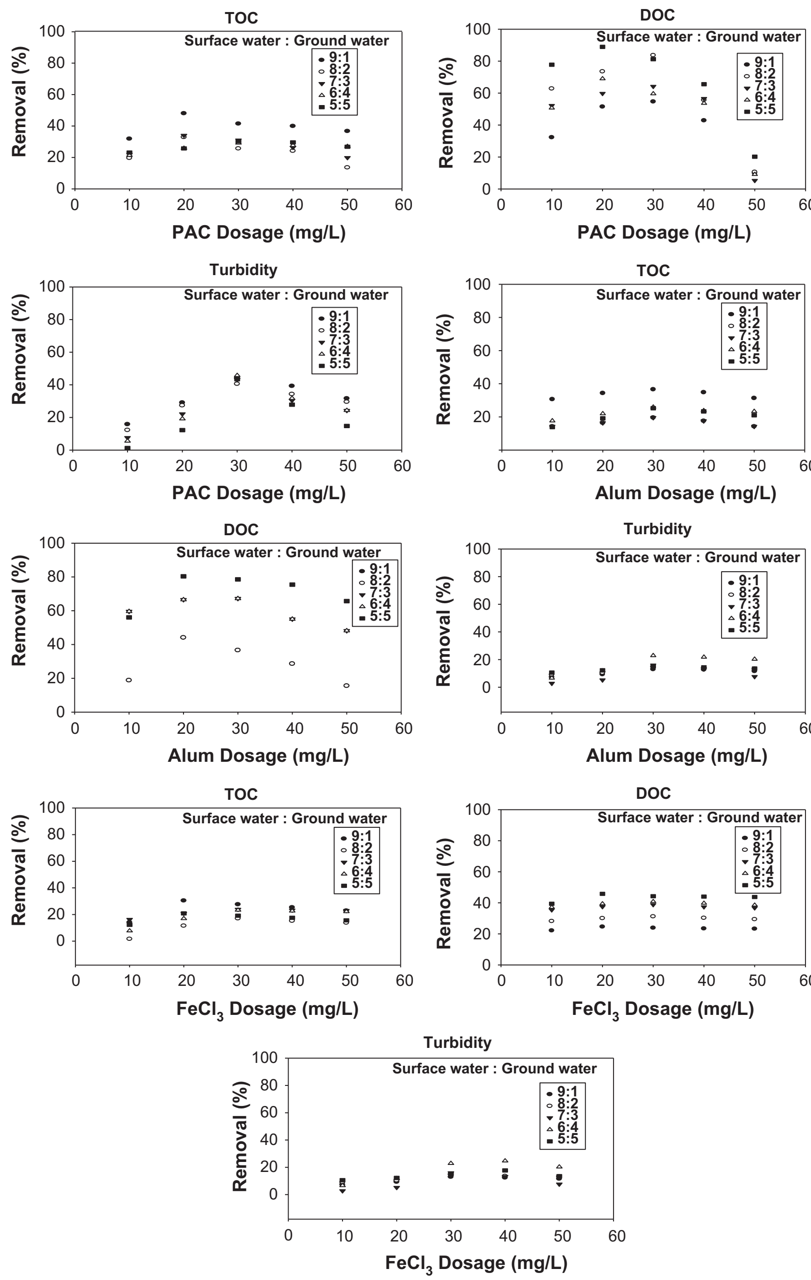

Fig. 3. Coagulation analysis based on TOC, DOC, and turbidity with different surface and ground water blending ratios.

In Fig. 5, the optimal dosage was defined at 20 mg/L, based on the TOC, DOC, and turbidity removal results for PAC dose. At dosages of 10–50 mg/L, the TOC concentrations were degraded with increasing ratios of rainwater. DOC removal was 49–51% (9.5:0.5), 48–56% (9:1), 50–55% (8.5:1.5), 44–45% (8:2), and 49–54% (7.5:2.5). At a 30 mg/L PAC dose, the turbidity removal was 82–88% (9.5:0.5), 86–91% (9:1), 85–90% (8.5:1.5), 80–86% (8:2), and 88–89% (7.5:2.5).

With alum, the TOC removal was 40–44% (9.5:0.5), 42–44% (9:1), 40–45% (8.5:1.5), 37–45% (6:4), and 43–49% (5:5). The DOC removal was 30–35% (9.5:0.5), 30–33% (9:1), 27–37% (8.5:1.5), 21–34% (8:2), and 35–45% (7.5:2.5), and the turbidity removal was 62–69% (9.5:0.5), 63–67% (9:1), 64–68% (8.5:1.5), 57–66% (8:2), and 66–80% (7.5:2.5). As the removal rates for TOC, DOC, and turbidity did not notably increase after the 30 mg/L alum dosage shown in Fig. 2, the optimal dosage was selected to be 30 mg/L.

Table 3
Characteristics of treated sewage water and rainwater with different blending ratios

Blending proportion Treated sewage water: rainwater	Analysis data					
	Temperature (℃)	pH	Conductivity (μS/cm)	Turbidity (NTU)	TOC (mg/L)	DOC (mg/L)
9.5:0.5	20	7.39	673	9.72	7.15	4.601
9:1	20	7.37	637	9.38	7.103	4.471
8.5:1.5	20	7.37	622	9.14	6.941	4.412
8:2	20	7.36	591	8.52	6.723	4.219
7.5:2.5	20	7.52	582	8.32	6.276	4.172

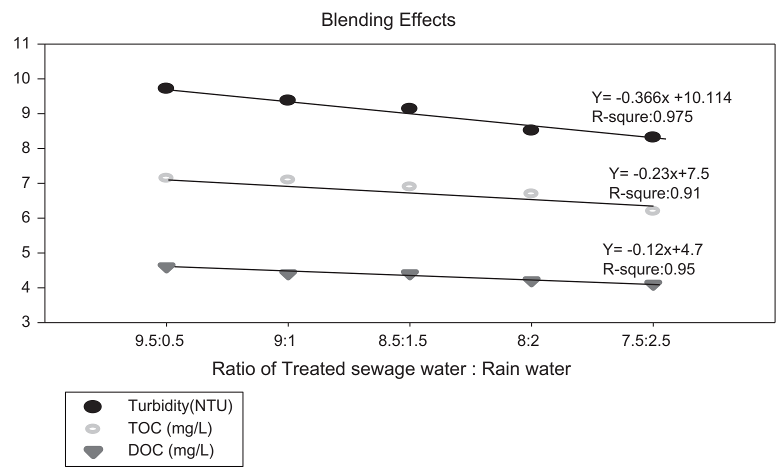

Fig. 4. Blending effects on turbidity, TOC, DOC parameters using treated sewage water and rain water.

In the $FeCl_3$ dosage range of 10–50 mg/L, the TOC removal was 31–33% (9.5:0.5), 39–42% (9:1), 40–54% (8.5:1.5), 41–49% (8:2), and 37–46% (7.5:2.5). The DOC removal was 14–18% (9.5:0.5), 26–30% (9:1), 27–48% (8.5:1.5), 27–41% (8:2), and 27–28% (7.5:2.5). The turbidity removal was 45–53% (9.5:0.5), 59–62% (9:1), 63–74% (8.5:1.5), 61–76% (8:2), and 60–73% (7.5:2.5). Based on these results, the optimal dosage of $FeCl_3$ was determined to be 30 mg/L since the 40–50 mg/L dosages did not notably increase the TOC, DOC, and turbidity removal.

In the experiment, used water samples have generally high turbidity, TOC, and DOC concentrations obtained by dosing with three different coagulants. The highest removal of TOC, DOC, and turbidity was found at a treated sewage water blending and rain water ratio of 8.5:1.5. Shahin et al. studied COD, turbidity, and color, and total suspended solid (TSS) removal efficiencies using PAC and alum in leachate water and found that COD, turbidity, color, and TSS removal efficiencies of 43.1, 94.0, 90.7, and 92.2% for PAC, and 62.8, 88.4, 86.4, and 90.1% for alum were demonstrated [13]. As comparing to our results, we found that high turbidity water could deliver high removal efficiency. The optimal dosage for each coagulant was found to be 20 mg/L for PAC, 30 mg/L for alum, and 30 mg/L for $FeCl_3$. Overall, PAC delivered the best performance among three coagulants, at a 20 mg/L coagulant dose.

3.3. Coagulation effects for blended waters comprised of sea water, brackish water, and rainwater

The purpose of this experiment was to lower the salinity of seawater by blending brackish water and rainwater in order to reduce the load pressure in seawater reverse osmosis (SWRO) to decrease maintenance and operating costs, and therefore to determine the optimum coagulant and its dose. Seawater, brackish water, and rainwater were blended at ratios of 8.8:1.0:0.2, 7.6:2.0:0.4, 6.4:3.0:0.6, 5.2:4.0:0.8, and 4.0:5.0:1.0. Blending ratios in the experiment were

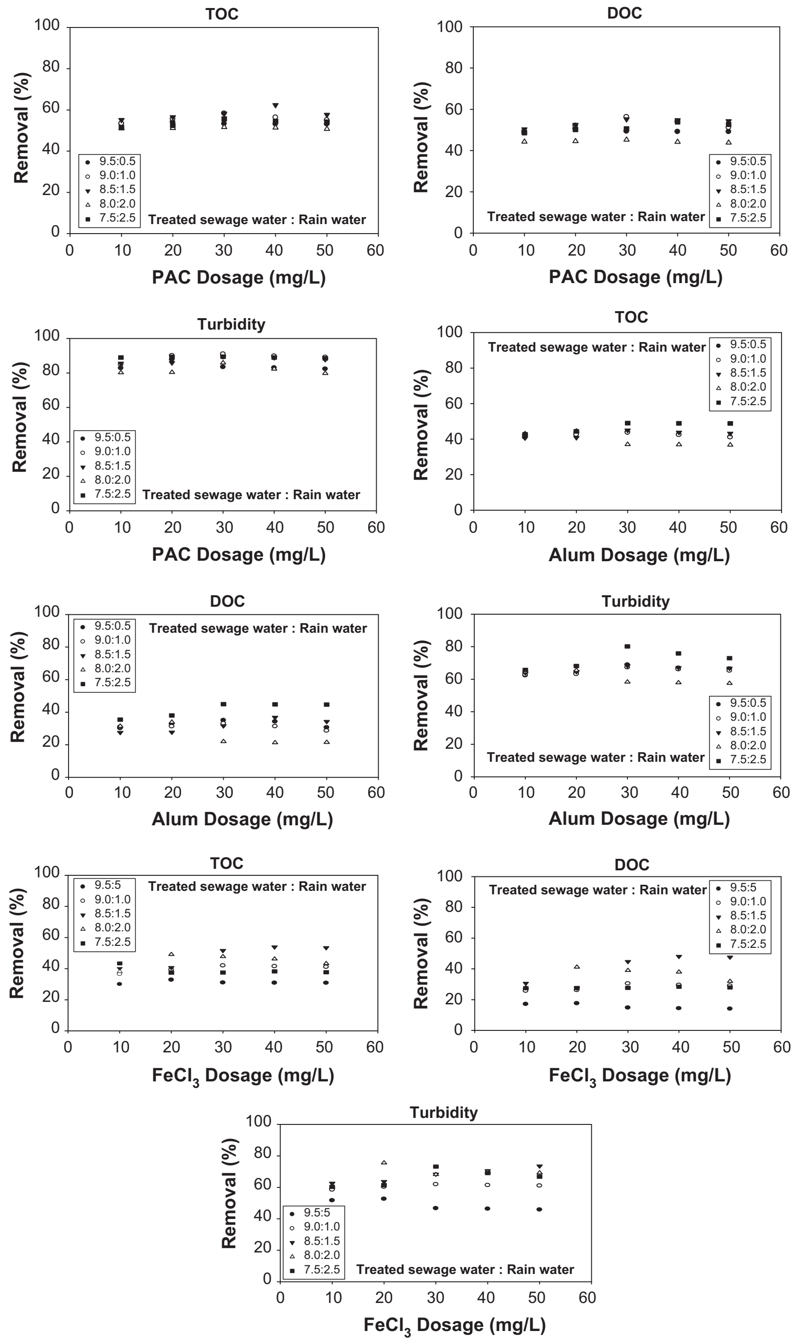

Fig. 5. Coagulation analysis based on TOC, DOC, and turbidity with different blending ratios of treated sewage water and rain water.

determined based on lowering salinity of seawater. Table 4 displays the water qualities of each blended water sample.

In Fig. 6, total dissolved solids (TDS) decreased proportionally by increasing brackish water and rain water. This indicates that blending brackish water and rainwater provide lowering salinity in desalination process. Low salinity could provide low osmotic pressure for low energy consumption in SWRO process [14]. In contrast, turbidity, TOC, and DOC increased by rising brackish water and rain water proportions.

At 10–50 mg/L doses of PAC, the TOC removal was 31–37% (8.8:1.0:0.2), 28–43% (7.6:2.0:0.4), 13–18% (6.4:3.0:0.6), 5–13% (5.2:4.0:0.8), and 10–17% (4.0:5.0:1.0).

Table 4
Quality of seawater, brackish water, and rainwater at different blending ratios

Blending proportion Seawater: brackish water: rainwater	Analysis data					
	Temperature (℃)	pH	Salinity (g Nacl/L)	Turbidity (NTU)	TOC (mg/L)	DOC (mg/L)
8.8:1.0:0.2	19	8.02	24	4.52	1.975	1.746
7.6:2,0:0.4	19	7.96	19	4.69	2.572	2.282
6.4:3.0:0.6	19	7.84	17	4.72	3.169	2.879
5.2:4.0:0.8	19	7.75	14.5	4.84	3.766	3.476
4.0:5.0:1.0	19	7.69	9.2	5.18	4.363	4.073

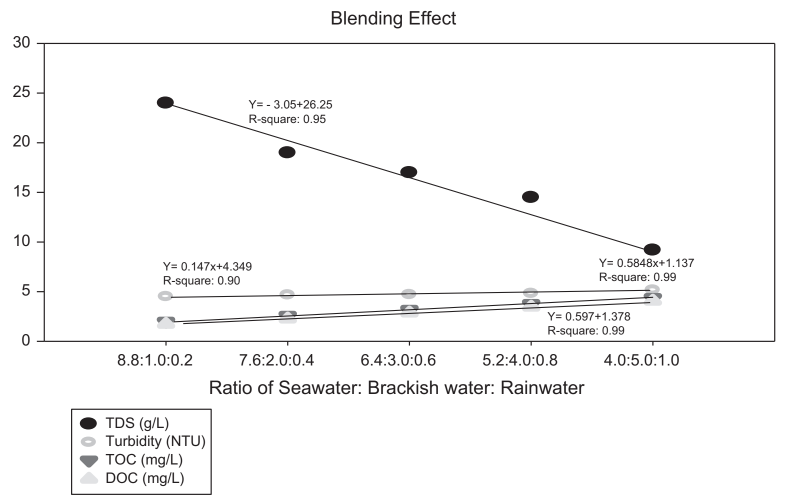

Fig. 6. Blending effects on turbidity, TOC, DOC parameters using surface water and ground water.

The DOC removal was 24–50% (8.8:1.0:0.2), 21–41% (7.6:2.0:0.4), 18–37% (6.4:3.0:0.6), 19–30% (5.2:4.0:0.8), and 30–35% (4.0:5.0:1.0). The turbidity removal was 62–68% (8.8:1.0:0.2), 54–66% (7.6:2.0:0.4), 46–64% (6.4:3.0:0.6), 39–61% (5.2:4.0:0.8), and 41–55% (4.0:5.0:1.0). The salinity removal was only 4–13% regardless of the PAC dosage. The optimal PAC dose was estimated to be around 20 mg/L based on the TOC, DOC, and turbidity removal.

In the alum dose range of 10–50 mg/L, the TOC removal was 21–25% (8.8:1.0:0.2), 30–37% (7.6:2.0:0.4), 9–19% (6.4:3.0:0.6), 5–11% (5.2:4.0:0.8), and 5–15% (4.0:5.0:1.0). The DOC removal was 16–23% (8.8:1.0:0.2), 14–22% (7.6:2.0:0.4), 9–21% (6.4:3.0:0.6), 14–25% (5.2:4.0:0.8), and 16–30% (4.0:5.0:1.0), and the turbidity removal was 30–59% (8.8:1.0:0.2), 26–60% (7.6:2.0:0.4), 16–58% (6.4:3.0:0.6), 18–55% (5.2:4.0:0.8), and 18–51% (4.0:5.0:1.0). The salinity removal was 2–21% regardless of alum dose; the optimal dosage was selected to be about 30 mg/L.

For a $FeCl_3$ dose of 10–50 mg/L, the TOC removal was 3–15% (8.8:1.0:0.2), 44–57% (7.6:2.0:0.4), 10–22% (6.4:3.0:0.6), 3–18% (5.2:4.0:0.8), and 12–26% (4.0:5.0:1.0). The DOC removal was 3–31% (8.8:1.0:0.2), 1–13% (7.6:2.0:0.4), 10–16% (6.4:3.0:0.6), 2–19% (5.2:4.0:0.8), and 12–26% (4.0:5.0:1.0). The turbidity removal was 26–35% (8.8:1.0:0.2), 30–45% (7.6:2.0:0.4), 35–45% (6.4:3.0:0.6), 22–46% (5.2:4.0:0.8), and 24–63% (4.0:5.0:1.0). The salinity removal was estimated to be within 4–23% regardless of the $FeCl_3$ dose. Based on these results, the optimal $FeCl_3$ dose was found to be about 30 mg/L.

As shown in Fig. 7, the salinity removal for the three different coagulants was low at dosages of 10–50 mg/L, indicating that salinity was not removed by coagulation. While salinity in each blending water sample is not a generally considered variable for selecting a suitable coagulant and its dosage, the blending process reduced more than half of the salinity in seawater. Hamidreza and Parvin [15] conducted

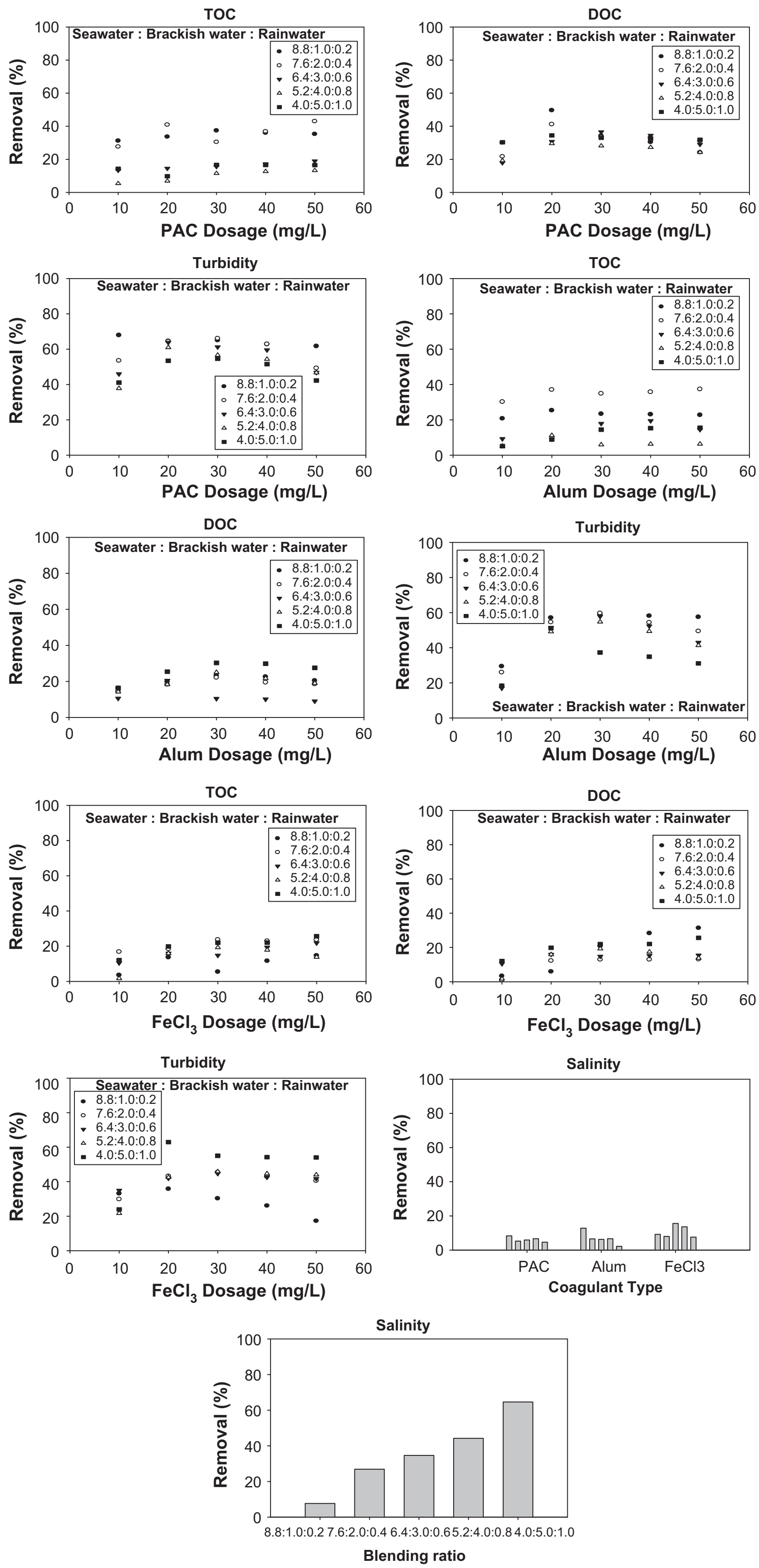

Fig. 7. Coagulation analysis based on TOC, DOC, turbidity, and salinity with different blending ratios of seawater, brackish water, rainwater, and ground water.

the experiment about the effect of coagulant dosage on coagulation process. They found that under optimal conditions of process parameters, a coagulant dose of 10 mg/L was efficient to remove 78 and 88% of the effluents' color by $FeCl_3$ and PAC, respectively [15]. In our experiment, the TOC, DOC, and turbidity were efficiently removed at 20–30 mg/L coagulant doses. The optimal dosages of $FeCl_3$ and alum sulfate dosage were found at 30 mg/L. Twenty milligram per liter of PAC dose were delivered the highest removal among 10–50 mg/L doses. In the experiment, high concentrations of turbidity, TOC, and DOC found more removal than low concentrations of all by blending rain water. Overall, based on economical and efficient removal aim, PAC was determined the optimal coagulant of all.

4. Conclusion

In this paper, three main experiments were performed using multiple water resources. First, various ratios of blended surface water and ground water were treated with 10–50 mg/L dosages of alum, PAC, and $FeCl_3$ to determine optimum turbidity, TOC, and DOC removal. In this experiment, PAC displayed the best performance in terms of coagulation at 30 mg/L, and the effect on blending water samples showed a higher removal efficiency that increased with the groundwater blending ratio. Second, when blending treated sewage water and rainwater, the removal efficiency of TOC, DO, and turbidity was the highest for a PAC dosage of 20 mg/L; alum and $FeCl_3$ displayed satisfactory removal rates at a dosage of 30 mg/L. The highest removal of TOC, DOC, and turbidity was found to be at a blended treated sewage water and rain water ratio of 8.5:1.5 due to high polluted water use. Finally, in the seawater, brackish water, and rainwater blending experiment, the turbidity, TOC, and DOC were efficiently removed at a dosage of 20–30 mg/L, and PAC was again determined to be the best of the three coagulants. For salinity removal, all three coagulants displayed a low removal efficiency of only up to 23%, and the blending process reduced 55% of the salinity at a blending ratio of 4.0:5.0:1.0.

This study determined an optimal coagulant and its dosage for various multiple water resources. Since the world water resources are limited and water demands are increased, it will be necessary to make greater use of multiple water resources in the near future. The outcomes of these experiments were applied to optimize the pilot water treatment plant requiring the use of multiple sources.

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