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Characteristics of pharmaceuticals removal in the sewage treatment process

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ABSTRACT

This study was designed to analyze pharmaceuticals removal using biological sewage and wastewater treatment processes. Since pharmaceutical removal efficiency in a bioreactor was very low, it was determined that removing pharmaceuticals using biological treatment alone is very difficult. Thus, it attempted to identify the pharmaceutical removal characteristics with main physical and chemical processes such as coagulation sedimentation, ozonation, activated carbon treatment, and chlorine disinfection process as targets. The removal efficiency by coagulation and sedimentation turned out to be highest in atenolol with 16%. Other substances exhibited low removal rates regardless of coagulant dosage. Results of the batch test in which 30 mg/L of ozone was injected stepwise showed that diclofenac and trimethoprim showed a 95% removal rate at an ozone concentration of 5 mg/L, while iopromide with the lowest processing efficiency exhibited a 90% removal rate at a high ozone concentration of 30 mg/L. The same trend was found in the activated carbon adsorption process in that substances such as iopromide and mefenamic acid showed satisfactory removal rates at EBCT = 15 min.

Keywords: Sewage treatment plant; Pharmaceuticals; Ozone oxidation; Activated carbon adsorption

1. Introduction

In today's modern society, various chemicals are being used in many aspects of people's lives. Among the more than 33 million kinds of chemicals registered in Chemical Abstracts Service of the American Chemical Society, more than 240,000 kinds are currently being distributed worldwide [1]. In this connection, the various chemicals exposed to the environment can cause several problems for humans and for the ecosystems. Due to the recent development of analytical techniques, the microcontaminants that used to be impossible to detect can now be analyzed, and the impact of microcontaminants on the ecosystem has

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emerged as a social issue [2–6]. In a related move, developed countries such as the United States have strengthened their standards for the residual allowable concentration of microcontaminants in the environment, have established analytical methods for the contaminants that have become emerging concerns, and have come up with risk assessment methods [7]. To date, 24 kinds of hazardous substances have been designated as specified substances harmful to the water quality in South Korea, and emission standards for 19 kinds have been established and managed. As water pollution accidents caused by microcontaminants without management standards for 1,4 dioxane and perchlorate frequently occur in the Nakdong River basin, an overall investigation of the emerging contaminants discharged by industrial companies is urgently required.

The representative kinds of emerging microcontaminants include pharmaceuticals, cosmetics, perfumes, and veterinary medicines. Among these, pharmaceuticals are important materials because they are being used in various sectors of the modern society, including hospitals and pharmacies as well as livestock and fisheries. Such pharmaceuticals, however, which are conveniently used, have been discovered in various water environments, such as surface water, groundwater, and soil, and when exposed to the water environment, they can cause a variety of risks. As such, relevant researches are under way [8–14].

Although the amounts of pharmaceuticals are small enough to be measured in ppm and ppt, they have steadily been discharged, and it has been reported that they are likely to continuously affect the aquatic ecosystems without causing high resistance, due to their low concentrations [15]. To date, there have been no reports on their direct impact on the human body, but a study was reported on the effects of pharmaceuticals introduced into the sewage treatment plant effluents on the propagation of fishes [16]. As pharmaceuticals are biologically active substances intended for specific pharmacological effects, the problems that occur from their exposure to the ecosystem cannot be ignored.

As there is a wide variety of routes in which these pharmaceuticals are introduced into the environment, it is difficult to figure out their behaviors, but most of them are gathered in sewage and wastewater treatment plants (WWTPs). The detailed mechanism, however, by which pharmaceuticals with various physical and chemical properties are removed is not yet known. In addition, as the existing treatment processes were not designed for the removal of pharmaceuticals, it is difficult to eliminate pharmaceuticals completely using such processes [17]. Previous studies reported that when conventional biological treatment methods are used, efficiency of pharmaceuticals removal is low with less than 58%. Some substances (erythromycin, TCEP, trimethoprim, naproxen, diclofenac, and carbamazepine) are difficult to remove even with the use of membranes such as MBA, and RO or NF to indicate removal efficiency of 95% or more [18–21]. There are reports on the biological treatment of pharmaceuticals indicating that diatrizoate is converted to 3,5-diamino-2,4,6-triodobenzoic acid [22] and diclofenac is converted to p-benzoquinone imine of 5-OH diclofenac [23]. Though removal of pharmaceuticals by ozone or advanced oxidation process is effective, it has been rarely reported due to economic reasons. It has also been reported that most of the pharmaceuticals are converted into low-molecular substances by ozone reaction with amines or phenols contained in the pharmaceuticals [24].

Consequently, this study examined the amount of pharmaceuticals removed through the actual removal process, and for this, large sewage and WWTPs were selected. In addition, this study attempted to propose baseline data for the management directions of sewage treatment plants by identifying the characteristics of the pharmaceuticals removed depending on the operating conditions, such as the coagulation, sedimentation, ozonation, activated carbon treatment, and chlorination processes, which are mainly being used in the current treatment plants, through laboratory experiments with the raw water of the treatment plants as the primary target.

2. Experiment methods

2.1. Study samples

This study examined the removal characteristics of pharmaceuticals at the two large-scale wastewater treatment plants in the Nakdong River basin. First, the removal rates by process of the actual sewage WWTPs were investigated by determining the pharmaceutical concentrations removed by process in each treatment plant, and then the physical and chemical removal characteristics of the pharmaceuticals were examined by conducting a batch test after taking supernatant raw water from treatment plants A and B.

Fig. 1 shows the operational process and water intake points of treatment plants A and B, and Table 1 shows the changes in the general items for each process.

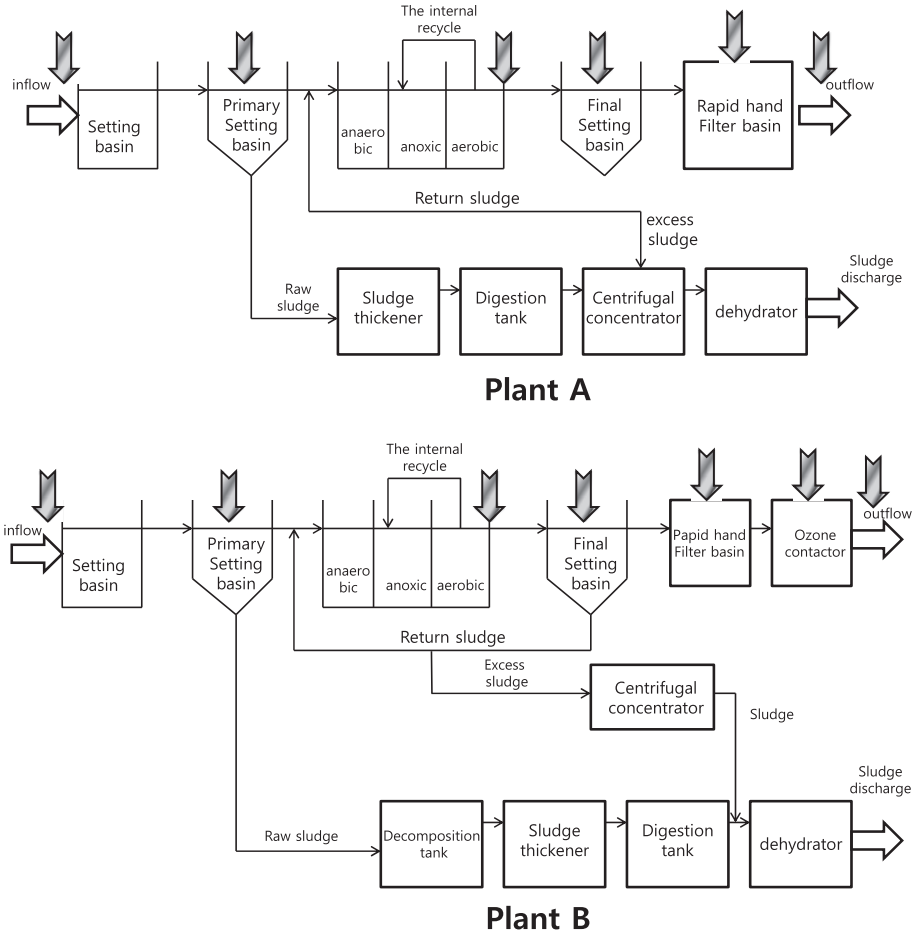

Fig. 1. Sampling points of sewage treatment plant A and B (⇩).

2.2. Analysis items and methods

2.2.1. Analysis items

The general water quality items were tested to investigate the basic characteristics of each treatment plant. A total of six items were analyzed by dividing pharmaceuticals into four categories: contrast media, anti-inflammatory analgesic drugs, beta-blockers, and antibiotics. The analysis items are briefly presented in Table 2.

2.2.2. Analytical methods

The general water quality indicators were tested in accordance with the official testing method with respect to the water pollution process. For the analysis of pharmaceuticals, 20 μL sulfathiazole-d_4, ibuprofen-$^{13}C_3$, the internal standard material for purification, was added to the samples after adjusting the pH to 3.5 using a 3.5 M H_2SO_4 solution. The samples were made to pass through an Oasis HLB (200 mg) cartridge after conditioning them by letting distilled water and methanol flow through them. The cartridge was washed with distilled water and was eluted with methanol. The eluent was concentrated with nitrogen gas, transferred to a brown vial, and analyzed with LC/MS/MS. All data shown in the figure refer to the mean value of experimental results repeated five times.

2.3. Experiment conditions

This study examined the pharmaceutical removal efficiency of coagulation, sedimentation, ozonation, activated carbon treatment, and chlorination at batch tests.

2.3.1. Coagulation–sedimentation

Table 3 shows the conditions of the coagulation and sedimentation experiments that were conducted in this study. For the coagulation experiment, the jar tester of Wisestir was used, and alum

Table 1
Variations of the water quality items in treatment plants A and B

	BOD	COD_{Mn}	T-N	T-P	SS	DOC
Plant A						
Influent	184.9	110.0	22.2	5.6	212.3	15.8
Primary clarifier	102.4	46.0	21.6	4.4	83.0	15.5
Aeration tank	322.3	510.0	76.5	26.1	1822.0	8.3
Final clarifier	11.2	6.6	7.6	1.4	2.8	5.1
Rapid filtration	5.1	4.6	6.7	1.2	1.6	4.2
Effluent	1.4	4.5	6.0	1.3	1.8	4.0
Efficiency (%)	99.2	95.9	72.7	76.6	99.2	74.7
Plant B						
Influent	149.7	88.0	31.7	3.9	148.0	29.1
Primary clarifier	82.3	39.0	29.6	2.5	84.0	34.0
Aeration tank	410.2	460.0	81.2	51.4	1490.0	20.1
Final clarifier	13.2	22.4	13.2	1.2	22.4	17.9
Rapid filtration	7.8	15.4	12.8	1.0	9.2	15.0
Ozone contactor	3.6	10.8	12.7	0.9	11.2	10.4
Effluent	3.9	10.2	11.7	1.0	7.6	9.9
Efficiency (%)	95.3	73.8	60.6	59.3	91.0	70.9
Water quality standard (2011)	10.0	40.0	20.0	2.0	10.0	–

Table 2
Target compounds in this study

Type	Compound
Contrast media	Iopromide
Anti-inflammatory analgesic drug	Mefenamic acid, diclofenac
β-blocker	Atenolol, propranolol
Antibiotics	Lincomycin, trimethoprim

Table 3
Coagulation experiment conditions

Item	Specifications
Coagulant	Alum ($Al_2(SO_4)_3{\cdot}18H_2O$)
Coagulant dosage	10, 20, 30, 40, 50 mg/L
Rapid mixing	1 min at 67 rpm ($G = 167\ s^{-1}$)
Slow mixing	10 min at 31 rpm ($G = 50\ s^{-1}$)
Sedimentation	30 min

($Al_2(SO_4)_3{\cdot}18H_2O$) with 8% Al was used as a coagulant. For the experiment, a 1 L beaker was filled with raw water, and the coagulant was gradually injected at the amounts of 10, 20, 30, 40, and 50 mg/L. After fixing the pH to 7 using NaOH and H_2SO_4, rapid mixing was done at 67 rpm for 1 min, and then slow mixing was performed at 31 rpm for 10 min. Analysis was conducted by collecting the supernatant water after settling for 30 min.

2.3.2. Ozonation

The ozone contact experiment is designed to determine the concentration of ozone by the amount of water coming out of the bottom, by injecting a certain amount of ozone into the inlet of the ozone demand flask filled with water samples. The ozone dosage was determined through the KI titration method, and ozone was injected at 5, 10, 15, 20, 25, and 30 mg/L concentrations. The volume of the demand flask was 1.5 L, and an experiment was conducted by means of the method to increase the contact efficiency of ozone by shaking the demand flask for 20 min after ozone injection.

2.3.3. Activated carbon treatment

The experiment conditions are shown in Table 4. For the pharmaceutical adsorption experiment using activated carbon treatment, a 23-mm-diameter and 350-mm-long column was used. Leakage of the activated carbon was prevented by installing a net at the lower layer of the column before filling the column with the activated carbon. The granular activated carbon was washed thoroughly with distilled water and was re-dried naturally after being dried in an oven for use in the experiment. The influent raw water was injected using a metering pump so that the flow would be downstream. The charge length of the activated carbon was 217 mm, and the experiment was

Table 4
GAC experiment conditions

Item	Specifications
Raw material	Coconut shell char
Column length	350 mm
Column ID	23 mm
Bed length	217 mm
EBCT	5, 10, 15 min
Flow rate	18, 9, 6 mL/min
LV	2.6, 1.3, 0.87 m/h

performed by changing the empty bed contact time (hereafter referred to as "EBCT") to 5, 10, and 15 min. After completing each experiment, the following experiment was conducted by replacing the activated carbon. A separate backwash was not performed.

2.3.4. Chlorination

Chlorine was injected at the amounts of 5, 10, 15, and 20 mg/L by measuring the available chlorine in the sodium hypochlorite solution and calculating its equivalent chlorine amount. For the chlorine contact experiment, the water samples were stirred for more than 15 min by injecting chlorine by degrees after filling a 2 L mass cylinder with it.

3. Results and discussion

3.1. Changes in concentration through the sewage and wastewater treatment process

The variation in the concentrations of the pharmaceuticals in each process of treatment plants A and B, which are currently being operated, were investigated to determine the extent to which pharmaceuticals are removed in the actual plants, and which process effectively removes them (Fig. 2).

In the case of the contrast media ioprimide, its removal efficiency was found to be about 77% through the bioreactor in treatment plant A, and there was minimal removal progress in the later process. In the case of treatment plant B, approximately 70% of the contrast media was removed in the aeration tank, and most of it was removed in the ozone contactor. The overall treatment efficiency turned out to be 97.6%.

For mefenamic acid, an anti-inflammatory analgesic drug, 24.1% of it was removed from the aeration tank of treatment plant A, and about 44% of it was removed through the rapid filtration process. In the case of treatment plant B, the removal efficiency of the bioreactor was low (11.1%), but a higher removal rate (94.4%) compared to the influent concentration was found in the ozone reactor. Diclofenac was not removed at all from the whole process of treatment plant A to the rapid filtration process of treatment plant B, but it was completely removed through the ozone contactor in treatment plant B.

As for atenolol, a beta-blocker, 33.3% of it was removed in the bioreactor of treatment plant A, and a 45% total insufficient removal rate was achieved through the whole process. In treatment plant B, about 50% of it was removed in the bioreactor, about 70% through the final sedimentation basin, and 95.9% through contact with ozone in the latter part. The atenolol was finally discharged at concentration of 0.007 μg/L.

In the case of the lincomycin, an antibiotic, there was no further removal after 54.5% of it was removed in the aeration tank in treatment plant A. Even in treatment plant B, up to 46.9% of it was removed until rapid filtration, but it was completely removed through the ozone contactor. Trimethoprim was also not removed after 25.6% of it was removed in the bioreactor in treatment plant A, but it was completely removed in the ozone contactor after 25% of it was removed in the bioreactor of treatment plant B.

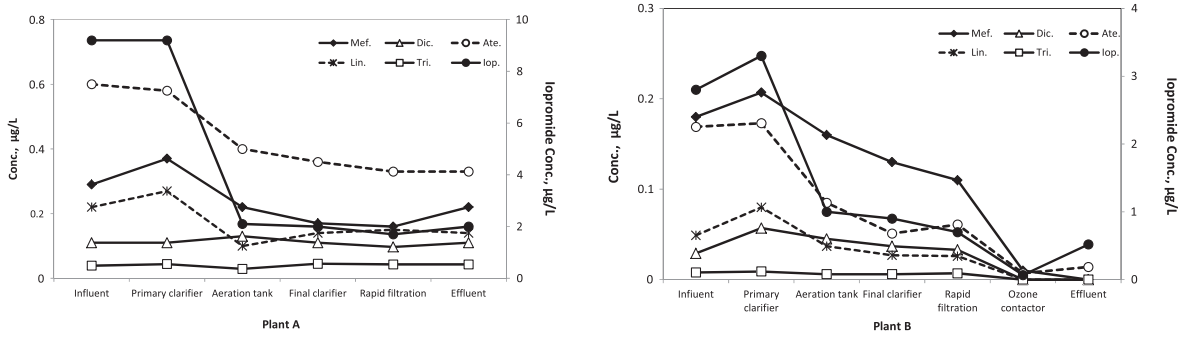

Fig. 2. Pharmaceutical concentration variations in sewage treatment plants A and B.

It was found in this study that some pharmaceutical substances were removed in the bioreactor, which indicates that they are simply biodegraded by micro-organisms. It is possible, however, that as pharmaceuticals are manufactured to produce specific effects in the bodies of humans and animals, and they are likely to be metabolized even by the micro-organisms in the reactor for pharmacological effects. This has been proven by the fact that pharmaceuticals can be present after being absorbed or combined with MLSS in the aeration tank, or after being dissolved by the organic substances and suspended solids in water [25], and the concentrations of pharmaceuticals decrease slightly more in the final sedimentation tank after the processing in the reactor. Meanwhile, although some of the pharmaceuticals are removed in the bioreactor, it is premature to conclude that the toxicity of the residual pharmaceuticals is completely removed because unpredictable metabolites with toxicity can be generated during the biological treatment process [26–28].

According to the previous researches, pharmaceuticals are decomposed by oxidants such as OH radicals generated by the reaction of photoresists such as nitrate and humic acid that exist in water with sunlight [29,30]. This result reinforces the point that pharmaceuticals are decomposed by ozone oxidation, which destroys pollutants through indirect reaction using OH radicals in addition to direct reaction. Other research also showed the superior efficiency of ozone treatment, as shown in this study. More than 90% of the mefenamic acid and diclofenac were removed when 2 mg/L ozone was injected, and more than 80% of the atenolol was also removed. Lincomycin and trimethoprim were completely removed when 2 mg/L ozone was injected [31]. Although there are various kinds of pharmaceuticals, and although the characteristics of each of them and their degradation rates vary, it was clearly shown in this study that the concentrations of pharmaceuticals are decreased by the ozone contactor.

3.2. Changes in concentration through batch tests

In treatment plants A and B, which are actually being operated, some of the pharmaceuticals were removed in the bioreactor, and most of them were removed by the ozone contactor. As photolysis by sunlight has various effects [29,30,32], however, such as attachment to the suspended solids present in the process or reaction with the precursors existing in the water, it is considered premature to conclude which process most effectively decomposes pharmaceuticals. Accordingly, a batch test was conducted to determine if the pharmaceuticals are physically treated by coagulation, sedimentation, and activated carbon adsorption or are chemically treated by ozone oxidation and chlorine contact.

3.2.1. Coagulation–sedimentation

The results of the coagulation and sedimentation experiments using alum in the raw water of treatment plants A and B showed that the pharmaceuticals were not removed regardless of the characteristics of the raw water and the coagulant dosage (Fig. 3).

In test 1, 16% atenolol was removed when 30 mg/L alum was injected. In test 2, 10% ioprimide was removed when 10 mg/L alum was injected, and 11% mefenamic acid was removed when 50 mg/L alum was injected. As for the remaining items, the pharmaceuticals were not removed regardless of the coagulant dosage.

The above results lead to the conclusion that it is difficult to remove pharmaceuticals through the coagulation and sedimentation processes alone, using alum, and additional processes are needed to achieve

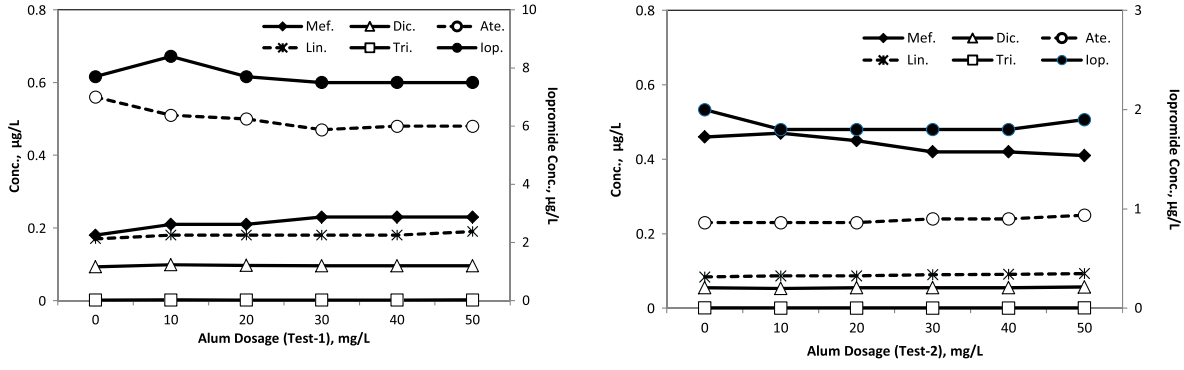

Fig. 3. Pharmaceutical concentration variations in the jar test.

higher removal efficiency. The study results confirmed that pharmaceuticals are not coagulated by alum, but as only experiments using alum were performed in this study, research must be conducted in the future to evaluate the pharmaceutical removal efficiency using various coagulants.

3.2.2. Ozone oxidation

Fig. 4 shows the results of the batch test in which 5–30 mg/L ozone was injected into raw water by degrees, using ozone demand flask. In the case of treatment plant A, to which domestic wastewater was introduced, more than 95% of the anti-inflammatory analgesic drugs diclofenac and trimethoprim were removed when 5 mg/L ozone was injected, and 100% was removed when 10 mg/L ozone was injected. More than 80% of the antibiotics lincomycin and mefenamic acid were removed when 5 mg/L ozone was injected, and 100% removal efficiency was achieved by injecting 10 mg/L ozone. Compared with the other pharmaceuticals, a larger amount of ozone had to be injected to remove atenolol due to its high influent concentration, but it was completely removed when 15 mg/L ozone was injected. Unlike other drugs, only 19% of iopromide, a contrast media, was removed when 5 mg/L ozone was injected. As the molecular weight of iopromide is 791.12 g/mol, and as it has a very complex chemical structure, slightly greater difficulty is expected in ozone oxidation compared to other substances. Ninety percent of it was removed, however, when 25 mg/L ozone was injected.

In the raw water of treatment plant B, to which industrial wastewater was introduced, diclofenac, lincomycin, and trimethoprim were well removed by 5 mg/L ozone, but iopromide and atenolol were not removed well even with the same ozone dose. In particular, mefenamic acid, which was well treated in treatment plant A, was found to show insufficient treatment efficiency in treatment plant B. These results indicate that some pharmaceuticals are not present in domestic wastewater, but ozone oxidation is interrupted by some of the materials contained by industrial wastewater.

In their research, pharmaceuticals with phenolic structures showed relatively high removal efficiency (78–99%) by ozonation [33]. This is because the OH group in the benzene ring activates the aromatic ring with its action as an electron donor so that the pharmaceuticals are easily oxidized by ozone, according to the previous results [33,34]. The six kinds of pharmaceuticals that were investigated in this study all have the form with benzene rings, and ozonation turned out to be very effective for their removal. Accordingly, if untreated pharmaceuticals flow into the Nakdong River basin, they can cause a variety of problems to the water environment. As such, the introduction of the ozone treatment process to the existing sewage and WWTPs needs to be reviewed.

3.2.3. Activated carbon adsorption

The activated carbon adsorption experiment was performed by changing EBCT to 5, 10, and 15 min (Fig. 5). The results of the activated carbon adsorption performance on the pharmaceuticals showed that nearly 100% of all the items, except for iopromide, were removed even at 5 min EBCT in test 1, and the rest of the items, except for iopromide and mefenamic acid, showed high removal efficiency (close to 100%) at 5 min EBCT in test 2. In addition, iopromide and mefenamic acid showed high removal rates (more than 70%) even at 5 min EBCT, and all the materials were removed at 15 min EBCT.

These results suggest that although there are differences in removal efficiency depending on the kind of pharmaceutical and the properties of the influent raw water, activated carbon has a very large effect on

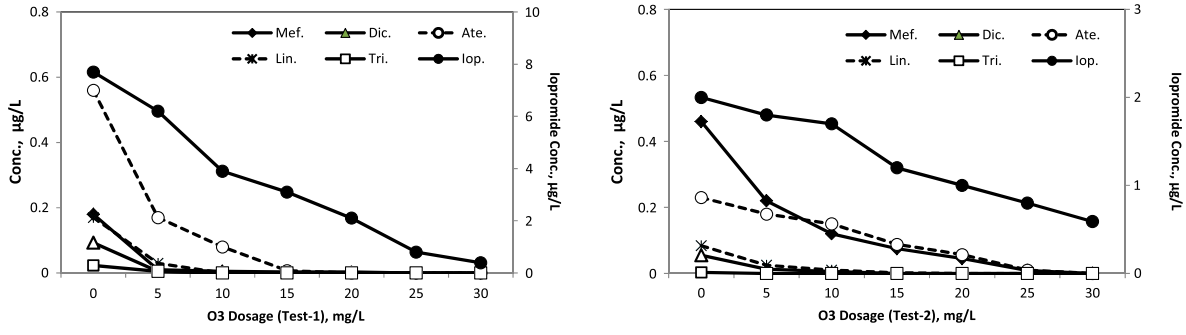

Fig. 4. Pharmaceutical concentration variations with O_3.

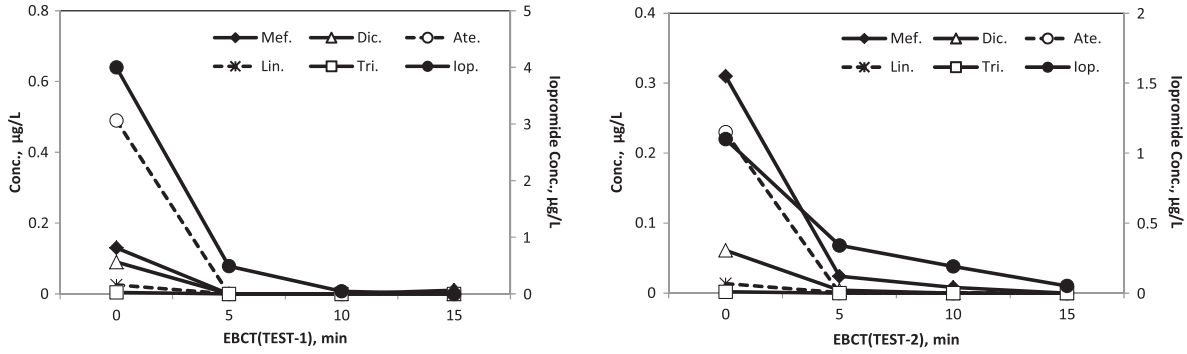

Fig. 5. Pharmaceutical concentration variations with GAC.

the removal of pharmaceuticals. The results of a domestic research in which the removal efficiency of pharmaceuticals was tested using granular activated carbon also showed that the pharmaceuticals that are difficult to remove through the existing treatment processes can be effectively controlled through the granular activated carbon adsorption process, based on the test results that showed 93–99% removal rates at 15 min EBCT [35].

3.2.4. Chlorine contact

Fig. 6 shows the results of the experiment conducted by changing the chlorine dosage at 5, 10, 15, and 20 mg/L. The chlorine contact test results showed that the removal rates of the remaining items, except for lincomycin, were insignificant. Lincomycin was completely removed in the case where the chlorine dosage was 15 mg/L in tests 1 and 2. Mefenamic acid was rarely removed in test 1, but its concentration gradually decreased at 15 mg Cl_2/L in test 2, with plant wastewater as the target. On the other hand, the removal rate of atenolol, a beta-blocker, was only 4% in test 2, but its concentration gradually decreased when 15 mg/L chlorine was injected into the raw water in test 1, with domestic wastewater as the target, which means that when chlorine and pharmaceuticals react with each other, a substance that exists in the water interferes with this reaction process. In fact, there was a research report that said that the MOM that exists in water reacts with chlorine first during the chlorination process, thereby acting as a deterrent in the decomposition of the residual pharmaceuticals [36].

The removal efficiency of atenolol and mefenamic acid varies depending on the properties of the influent, but their removal rates were significantly low compared to those in the ozone oxidation and activated carbon adsorption in this study. Therefore, the removal efficiency by chlorine was difficult to expect for the rest of research targets, except for lincomycin, but it is considered useful to additional oxidation and disinfection through chlorination after other processes.

3.3. Optimal process for the removal of pharmaceuticals

According to the data gathered in this study, the removal rate of iopromide was about 70% in the biological treatment process, but that for the rest of the items turned out to be less than 25%. In addition, the removal rate was very low despite the rapid filtration process after going through the bioreactor, which

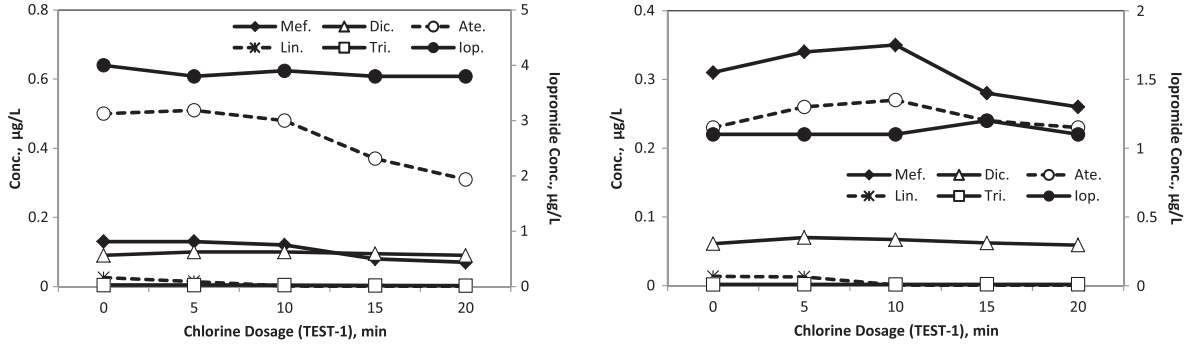

Fig. 6. Pharmaceutical concentration variations with chlorine treatment.

Table 5
Optimal processes for pharmaceuticals removal in sewage and WWTP

Process	Pharmaceutical					
	Iop.	Mef.	Dic.	Ate.	Lin.	Tri.
Bioreactor	△	—	—	×	—	×
Bioreactor + rapid filtration	○	×	—	△	—	×
Bioreactor + rapid filtration + ozone	◎	◎	◎	◎	◎	◎
Bioreactor + rapid filtration + ozone + activated carbon	◎	◎	◎	◎	◎	◎

Iop.: iopromide; Mef.: mefenamic acid; Dic.: diclofenac; Ate.: atenolol; Lin.: lincomycin; Tri.: trimethoprim.
—: 20%↓ removal; ×: 40%↓ removal; △: 70%↓ removal; ○: 90%↓ removal; ◎: 90%↑ removal.

indicates that these processes alone are not sufficient to remove pharmaceuticals.

On the other hand, when viewed from the results of treatment plant B, in which an ozone treatment facility was established, the addition of the ozone treatment facility to the follow-up process is expected to remove up to more than 90% of pharmaceuticals, which was reconfirmed in the batch test conducted in this study. It is expected that as the ozone treatment process oxidizes the organic substances that are difficult to decompose biologically into simple end products, and enables color treatment, it will be very useful to the sewage treatment process [37]. In addition, substances with large molecular weights, such as iopromide, are expected to be removed more thoroughly by adding the activated carbon adsorption process after offsetting the molecular combination through ozone treatment.

Accordingly, it is desirable to use the ozone oxidation and activated carbon processes for the effective control of pharmaceuticals that have various removal mechanisms due to their very complex physicochemical and biological properties. Based on the research results, the optimal process for removing pharmaceuticals in sewage and WWTPs was proposed (Table 5). As this study investigated only six items among the numerous kinds of pharmaceuticals used by humans, there is a need to carry out studies to determine the removal efficiency of various other materials.

4. Conclusions

Results of the investigation on changes in pharmaceuticals removal by the treatment plant process found that some of the pharmaceuticals are removed in the bioreactor, but their removal efficiency is low in most cases, which leads to the expectation that removal of pharmaceuticals using biological treatment process alone is difficult. As a result of the batch test on the influent of a treatment plant, removal by coagulation and sedimentation showed removal rates of less than 16% in all substances. The chlorine disinfection process succeeded in removing some of the pharmaceuticals, but it proved to be insufficient for use as a single process. Results of the batch test with 5–30 mg/L of ozone injected stepwise revealed that substances that are easy to be treated such as diclofenac and trimethoprim reached a removal rate of 95% at an ozone concentration of 5 mg/L. Iopromide, whose chemical structure is very complex with a molecular mass of 791.12 g/mol, showed a proportional trend with a removal rate of 19–90% at an ozone concentration of 5–30 mg/L. The same trend was found in the activated carbon adsorption process as iopromide and mefenamic acid exhibited a satisfactory removal rate of 95% or more at EBCT = 15 min. Thus, it is determined that physical and chemical processes such as ozonation and activated carbon adsorption process should be added to effectively remove pharmaceuticals that are difficult to remove using conventional biological treatment methods.

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