**Membrane and Water Treatment**, *Vol. 11, No. 2 (2020) 141-149*
DOI: https://doi.org/10.12989/mwt.2020.11.2.141


# Assessing the removal efficiency of *Synedra* sp. through analysis of field data from water treatment plants

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*(Received August 16, 2019, Revised November 11, 2019, Accepted November 14, 2019)*

**Abstract.** Prechlorination could increase the removal efficiency of *Synedra*, but there was no significant effect of increasing the amount of chlorine added. However, a removal efficiency of greater than 80% was noted when ozone was injected at concentrations greater than 2 mg/L. Also, it was found that on addition of polyamine, a removal efficiency of 80% or more could be achieved. As a result of the analysis of field operation data from the water treatment plants G and B, it was found that at water treatment plant G, the filter run time decreased to 10 hours or less when only coagulant was injected, but the filter run time increased to around 40 hours when polyamine (3 mg/L) was also injected. The *Synedra* population in the raw water subsequently increased to 2,340 cells/mL, and the filter continued running for more than 20 hours. At water treatment plant B, the average *Synedra* removal efficiency was 56% when only coagulant was injected, and the filter run time decreased drastically with the increasing population of *Synedra* in the raw water. However, the removal efficiency of *Synedra* reached 79% when polyamine was injected together with the coagulant, 90% when ozone was also injected, and 95% when polyamine and ozone were injected together and the filter continued running for over 50 hours. The filter run time was maintained at 60 hours when a *Synedra* population of 6,890 cells/mL flowed into the Paldang water source, but the filter run time with *Synedra* at 1,960 cells/mL decreased rapidly from 65 hours to 35 hours when the ratio of the size of the individual *Synedra* reaching 250 $\mu m$ or more, increased from 38% to 94%. Therefore, the size of the *Synedra* is considered to be a factor that significantly influences filter clogging, as well as the size of the *Synedra* population.

**Keywords:** *Synedra*; filter clogging; filter run time; polyamine, ozone

## 1. Introduction

Most of the rivers and lakes in Korea are dominated by diatoms from autumn to spring (Ha *et al.* 1995). The extensive growth of diatoms in water is known to cause a pH rise and, therefore, deviate from the optimum pH for flocculation (Lee *et al.* 2013). In particular, *Synedra* sp. is a diatom algae that is notorious for clogging filters during the water treatment processes (Kim *et al.* 2014). When large numbers of *Synedra* flow into water treatment plants, an accompanying decrease in the flocculation and sedimentation efficiency generally follows. This means that *Synedra* does not settle in the sedimentation basin and the untreated *Synedra* can flow into the filtration system. Filter run time is then decreased due to headloss increase. The degree of filter clogging varies depending on factors concerning the *Synedra* levels (population, size, etc.), filter composition, and various other factors (Kim *et al.* 2014).

When the filter run time is decreased due to the increase of *Synedra*, various problems can occur in the process of water treatment. If the backwash cycle is much shorter than usual, frequent backwashing will increase the volume of the effluent water, resulting in insufficient residuals treatment facility capacity, and may also cause problems in water production (Park 1999, Lim *et al.* 2000, Ha. 1999). If a large number of *Synedra* is present in water resource, the usage of the inorganic polymer coagulant, which is usually used to remove *Synedra* in existing water treatment plants, is limited for their removal (Gwak 1994). Consequently, the filters will inevitably become clogged and filter run time will be drastically reduced (Lee 2002). In recent years, incidences of abnormal water quality have increased because of climate change, and occurrences of *Synedra* in water have been increasing as well. As the utilization of water treatment plants increases, it has been more difficult to remove *Synedra* during treatment because of an increase in the surface loading rate and a decrease in the retention time at the sedimentation basin. Therefore, in order to effectively respond to the challenges in water treatment caused by *Synedra* in such plants, more thorough preparation is required. To increase the efficiency of the removal of *Synedra*, a dual filter system is often applied to improve the performance of the filtration; polyamine and coagulant aids can also be used to increase flocculation and sedimentation (Kim *et al.* 2014, Jun *et al.* 2001, Choi *et al.* 2003, Lee and Kim 2001, Park *et al.* 2001, Kim 2003).

The genus *Synedra* is found in various sizes, depending on the species. *Synedra* tenera. ranges 30–100 μm in length, *Synedra* acus. ranges 100–300 μm, and even members of the same species can vary between 40–500 μm, depending

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ISSN: 2005-8624 (Print), 2092-7037 (Online)

on the environment (Lee *et al.* 1996, Venkatachalapathy and Karthikeyan 2013). Therefore, by studying the methods used in water treatment processes to improve removal efficiency of *Synedra*, and through field data analysis, an optimal water treatment method for practical application that considers both the number and size of *Synedra* flowing into a water treatment plant was derived. This study was carried out with the aim of contributing to the stable production and supply of tap water.

## 2. Materials and Methods

In this study, the characteristics and efficiency of several processes used for the removal of *Synedra* at water treatment plants were investigated, and laboratory tests were performed using the raw water found at a specific water treatment plant. Laboratory tests were carried out to investigate the removal efficiency of *Synedra* using chlorine, ozone, coagulant, and polyamine injection on the raw water from water treatment plant G, located in the Nakdong River Basin, where an abundance of *Synedra* occurs naturally in the water source. In addition, the operational data for each treatment process—coagulant injection, chlorination, ozone treatment, and polyamine injection—applied to remove *Synedra*; the removal efficiency and the filter run times were analyzed and applied to the assessment to determine the optimal water treatment process.

### *2.1 Experimental Material*

Raw water used for this experiment was collected from water treatment plant G. PAHCS ($Al_2O_3$ 10.6%, basicity 73%) was used as a coagulant in the water treatment plant and polyamine (25.6%), registered as a water treatment agent, was used as coagulant aid. Chlorine was collected from the liquid chlorine container of water treatment plant and diluted to the concentration required for the experiment. The ozone was generated using a TRIOGEN LAB2B ozone generator.

### *2.2 Experimental Methods*

The removal efficiency of *Synedra* via the various water treatment processes was analyzed using the Jar-test (Jar-tester, Phipps & Bird, Inc.). Jar-test of each water treatment process was performed as follows. Experimental conditions of 300 rpm for 1 min (rapid mixing), 30 rpm for 10 min, 20 rpm for 10 min, and 10 rpm for 10 min (slow mixing) were carried out. After 30 min of sedimentation, the surface water was collected and tested for presence of *Synedra*.

The dose and contact time of each water treatment agents applied to the experiment were determined by considering the actual applicable concentration and contact time at the water treatment plant, and the range of the injection concentration and the experimental procedure were set by referring to the relevant literature (Oh *et al.* 2013).

In order to investigate the characteristics of *Synedra* removal by chlorine injection, the *Synedra* sample was concentrated to adjust the population to 1,018 cells/mL, and then injected with 60 mg/L of coagulant after the addition of 0-10 mg/L of chlorine.

To investigate the removal of *Synedra* by ozone injection, the *Synedra* sample was concentrated to adjust the population to 13,978 cells/mL, after which 3 mg/L of chlorine and 0–3 mg/L of ozone was injected. The Jar-test was then performed by injecting 60 mg/L of coagulant. Finally, to investigate the characteristics for the removal of *Synedra* by the addition of coagulant, the *Synedra* sample was concentrated to adjust the population to 1,047 cells/mL and 5,986 cells/mL, and 60 mg/L of coagulant was injected. Testing the removal of *Synedra* by polyamine injection was carried out by adjusting the *Synedra* population to 1,018, 5,986, and 16,973 cells/mL, which was then injected with 3 mg/L of chlorine, 60 mg/L of coagulant, and 0–10 mg/L of polyamine, respectively.

### *2.3 Analysis Method*

For the analysis of the *Synedra* population, the samples were added to a Sedwick-Rafter chamber by pipette and then examined using a Nikon optical microscope at 400×magnification, and the number of *Synedra* per mL was calculated. The samples were dried and coated with platinum for microscopic SEM (Scanning Electron Microscope) analysis performed using a S-3200N (HITACHI). The *Synedra* was stained with DAPI (4', 6-diamidino-2-phenylindole) to observe the morphology of the intracellular and nuclear parts of the *Synedra*, which was observed with a fluorescence microscope (80i, Nikon) (Shishlyannikov *et al.* 2011).

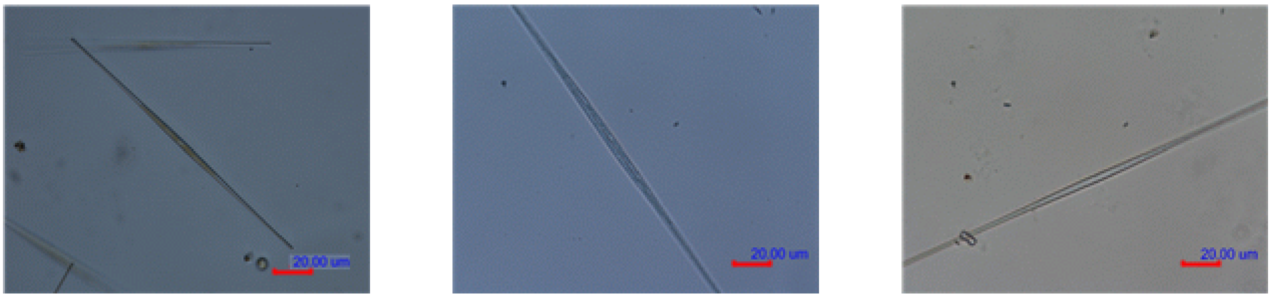
## 3. Results and discussion

### *3.1 Removal Characteristics by Oxidation(Chlorine and Ozone)*

When the oxidant is injected, it is apparent that the main constituents of the *Synedra* algae cell is released outside the cell, and the *Synedra* is removed by bridging, in a manner similar to that carried out via polymer. When chlorine is injected, the polysaccharides, which are the main constituents of the *Synedra* algae cells, are released in a similar manner (Gügi *et al.* 2015, Kates and Volcani, 1968). Fig. 1 shows that when *Synedra* is in contact with chlorine or ozone, intracellular substances are released from the cells, while in raw water *Synedra* retains the constituent materials of its cells. It is also apparent that more constituent materials are released when oxidized with ozone (MOE, 2017). This is because the redox potential of ozone ($O_3$) is 2.07 V, which is greater than the redox potential of chlorine(HOCl), at 1.49 V (Kelley 2004).

This means that the effect of oxidation with ozone is greater, as seen in Fig. 3.

Fig. 2 shows a change in the removal efficiency of *Synedra* as associated with the rate of chlorine injection when the coagulant (PAHCS, $Al_2O_3$ 10.6%, basicity 73%) was also injected.




(a) raw water (b) chlorine 3 mg/L, contact time; 2 h (c) ozone 1.5 mg/L, contact time; 1 min

Fig. 1 Intracellular material release due to chlorine and ozone oxidant

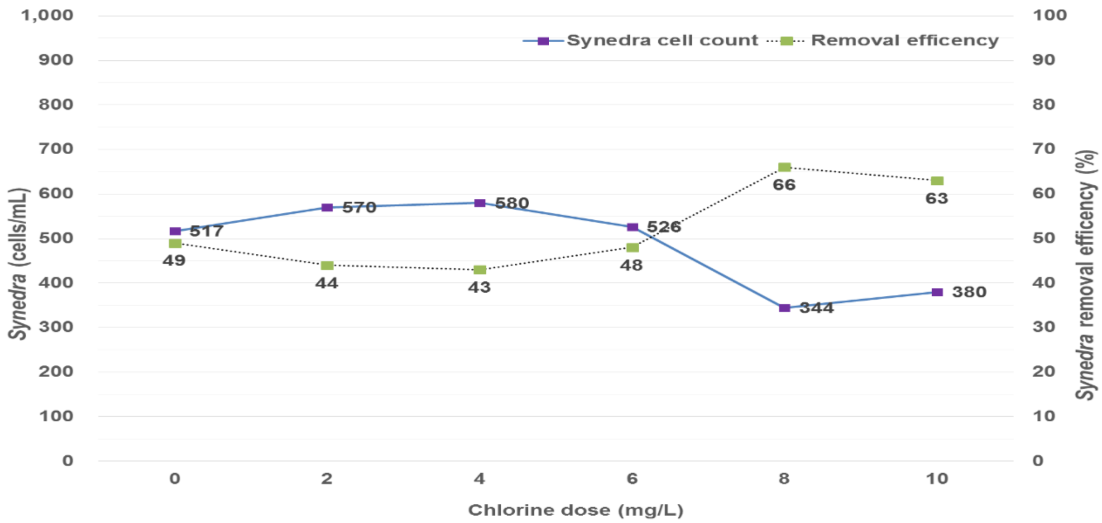



Fig. 2 Experimental results on *Synedra* removal efficiency by chlorine injection rate. (PAHCS injection rate: 60 mg/L)

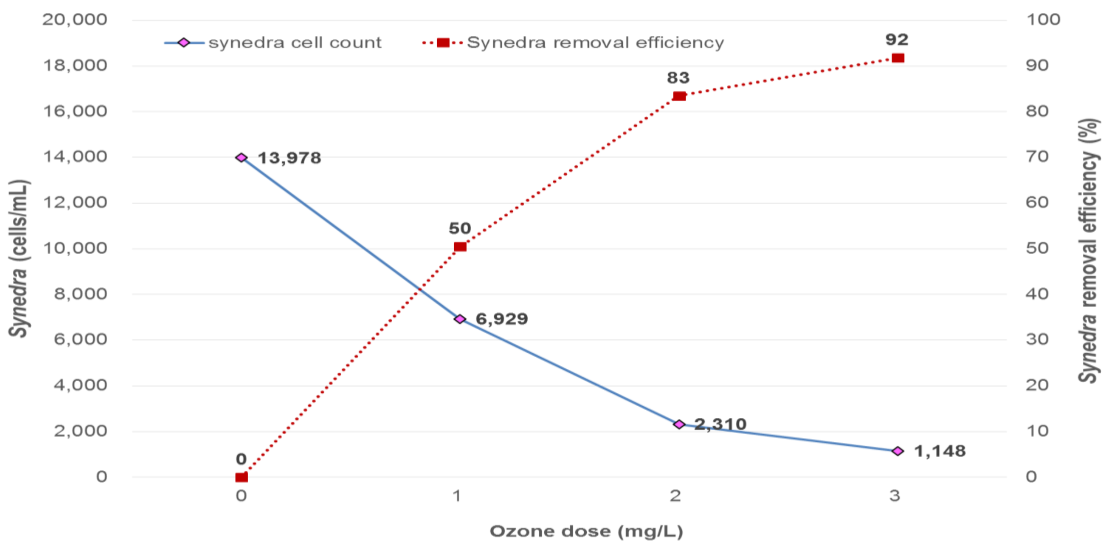



Fig. 3 Experimental results on *Synedra* removal efficiency by ozone injection rate(PAHCS injection rate: 60 mg/L )

As a result, it is suggested that the removal of *Synedra* can be increased by chlorine injection. However, the removal efficiency was not significantly different when the chlorine injection rate was increased. If the chlorine injection rate is increased to 8 mg/L, the removal efficiency can be increased to approximately 66%, but the addition of an increased amount of chlorine is problematic because of a corresponding increase in disinfection byproducts and difficulty in managing the residual chlorine concentration. Therefore, it is desirable to inject chlorine at a level that can remove both ammonia and nitrogen ($NH_3$-N) and maintain an acceptable residual chlorine concentration (0.1–0.2 mg/L) in the sedimentation basin without solely depending on increasing the chlorine injection rate for *Synedra* removal.

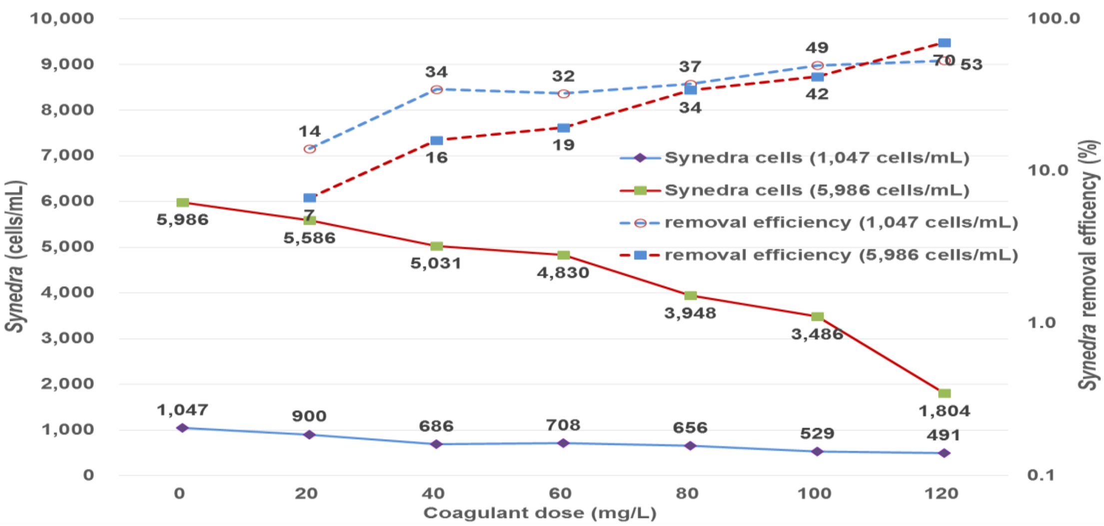



Fig. 4 Experimental results on *Synedra* removal efficiency by coagulant injection rate (PAHCS injection rate: 60 mg/L)

Ozone is more effective than chlorine because of its higher oxidizing power, but when excess ozone is injected, all the intracellular substances of *Synedra* are released (Plummer and Edzwald, 2002), resulting in low density and floatation. This could also lead to problems such as lowering the removal efficiency of *Synedra* and increasing the concentration of disinfection byproducts in drinking water (Chen *et al*. 2003). It is apparent from Fig. 3 that as the rate of ozone addition was increased, the *Synedra* removal efficiency also increased, to more than 90%. However, the removal efficiency was 80% or more even with the addition of only 2 mg/L. Therefore, as in the case of chlorine addition, it is desirable to use an appropriate amount, while taking into consideration the economic efficiency and conditions of the on-site facilities (operation rate, injectable concentration, availability of polyamines, etc.).

### 3.2 Removal characteristics by coagulation

Fig. 4 shows the experimental results for the removal of *Synedra* via the addition of coagulant. The efficiency in the removal of *Synedra* increased as the injection rate of the coagulant (PAHCS, $Al_2O_3$ 10.6%, basicity 73%) was increased. However, at the level of coagulant addition(20–40 mg/L), which is commonly applied in water treatment plants, the removal efficiency is only approximately 20–30%, depending on the *Synedra* population. If there is a large *Synedra* population in the raw water, achieving the target of less than 100 cells/mL in the influent at filtration is difficult with the addition of coagulant alone.

When the polyamine is injected with an oxidant to increase the coagulation efficiency by cross-linking, the settling velocity and the treatment efficiency of *Synedra* can be increased (Reynolds, 1984). This is because, after such treatment, the size of the flocs becomes large, the density is higher, and the shape is close to spherical. Fig. 5 shows the mechanism for removal of *Synedra* acus. using polymers. The shape coefficient ($\Phi_r$) of *Synedra* is 4.08, and the settling velocity is 4 times lower than that of spherical particles. However, when the polyamine is injected it becomes almost spherical, the shape coefficient (Φr) decreases, and the settling velocity increases.

As a result of the experiment carried out using polyamines, it was found that when the polyamine was injected during the process of flocculation and sedimentation, *Synedra* removal could be improved to more than 80%. The rate of polyamine injection to maintain a *Synedra* population of 100 cells/mL in the influent at filtration differs according to the number of *Synedra* in the raw water as shown in Table 1. As the number of *Synedra* in the raw water increases, the removal target was achieved by increasing the polyamine injection rate.

When determining the amount of polyamine to be injected, it is necessary to take safety factors into consideration. As seen in Fig. 6, polyamine is a colorless or pale yellowish brown liquid which is synthesized by the polycondensation of DMA (Dimethylamine) and EPI (Epichlorohydrin) (Lee *et al*. 2005); the concentration of epichlorohydrin in the water treatment process, therefore, needs to be considered when using this method.

According to the "standards, specifications, and labeling standards for water treatment agents" released by the Ministry of Environment, polyamines should be used at a concentration of 10 mg/L or less to limit the amount of epichlorohydrin in the water (MOE, 2017), and water treatment plants that use polyamines have to measure the concentration of epichlorohydrin in the water at least once a month.

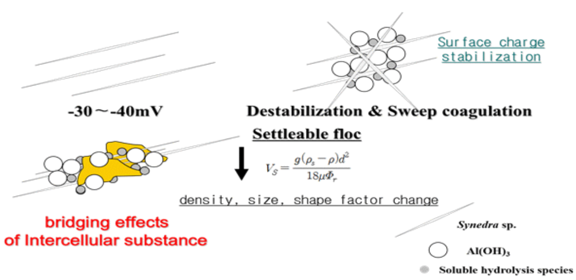



Fig. 5 Removal mechanism of *Synedra* by polymer use

Table 1 Removal characteristics by polyamine injection rate by *Synedra* population

| polyamine injection rate (㎎/L) | *Synedra* | | | | | |
|---|---|---|---|---|---|---|
| | number (cells/mL) | removal efficiency (%) | number (cells/mL) | removal efficiency (%) | number (cells/mL) | removal efficiency (%) |
| 0 | 1,018 | - | 5,986 | - | 16,973 | - |
| 0.5 | 333 | 67 | 5,250 | 12 | 14,461 | 15 |
| 1.0 | 210 | 79 | 5,246 | 12 | 14,832 | 13 |
| 3.0 | 168 | 83 | 861 | 86 | 8,275 | 51 |
| 5.0 | 168 | 83 | 126 | 98 | 1,537 | 91 |
| 10.0 | 43 | 96 | 294 | 95 | 126 | 99 |

Table 2 Criteria of Epichlorohydrin water quality by country

| WHO (recommendation) | Australia (health standards) | Japan (futher study) | EU (recommendation) |
|---|---|---|---|
| 0.4 μg/L | 0.5 μg/L | 0.4 μg/L | 0.1 μg/L |

Therefore, from the experimental results for epichlorohydrin concentration due to polyamine injection rate as seen in Fig. 7, polyamine should be injected at 6 mg/L or less to maintain a concentration of 0.1 ㎍/L of epichlorohydrin (EU criteria, see Table 2) in the water treatment process.

In addition, cationic coagulants such as polyamines increase the positive charge of the water as the concentration is increased (Yamashita *et al.* 2003). Therefore, if excess amount is added, the turbidity of the settled water could increase due to the charge reversal phenomenon. Therefore, when polyamine is injected, an acceptable rate of addition must be determined through the Jar-test.

### *3.3 Analysis of process operation data of water treatment plant*

When large numbers of *Synedra* occurred naturally in the water source and flowed into the treatment plant, the data from the treatment techniques used during water treatment to remove *Synedra* were analyzed to evaluate the relationship between the removal of *Synedra* and the run time of the filter. The study took place at water treatment plants G and B, situated on the main stream of the Nakdong River Basin, and the *Synedra* population, the characteristics of removal for each water treatment process, and the relationship between these factors and the filter run time were analyzed. As shown in Table 3, water treatment plants G and B use the most advanced treatment processes, using ozone and granular activated carbon (GAC) in addition to the standard water treatment processes. The water treatment plant G applies post-ozone, whereas water treatment plant B

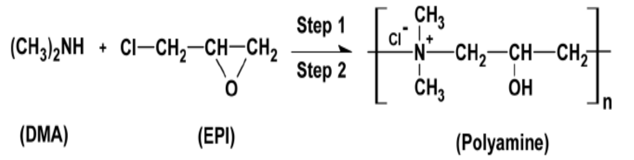



Fig. 6 Polyamine synthesis by polycondensation of Dimethylamine and Epichlorohydrin

Table 3 G and B Water Treatment Plant Facilities and Process Status in Nakdong River Basin

| Name of WTP | Capacity (㎥/d) | Drinking Water (㎥/d) | Industrial Water (㎥/d) | Type of Water Treatment | |
|---|---|---|---|---|---|
| | | | | Conventional | Advanced |
| G | 44,000 | 18,000 | 26,000 | Rapid Sand Filtration | Post-Ozonation $+H_2O_2$+GAC |
| B | 120,000 | 120,000 | - | Rapid Sand Filtration | Pre-Ozonation $+H_2O_2$+F/A |

has a pre-ozonation facility. Therefore, when *Synedra* occurs, oxidation treatment with ozone is possible.

Fig. 8 shows the number of *Synedra*, the polyamine injection rate, and the filter run time in the water treatment plant during the period from December 2013 to April 2014 when the bulk of the *Synedra* flowed into the G water treatment plant.

During this period, water treatment plant G decreased its filter run time to 10 hours even though the water treatment had been enhanced (coagulant PAHCS increased from 20-60 mg/L, and chlorine 2-3.7 mg/L) according to the increase in *Synedra* population. However, the filter run time increased to approximately 40 hours when 3 mg/L of polyamine was injected. The amount of polyamine injected was determined by Jar-test, taking into consideration the number of the *Synedra* in the raw water, after which the filter run time was increased to more than 20 hours even though the number of *Synedra* in the raw water had increased from 1,500–2,340 cells/mL.

When the coagulant alone was injected without the addition of polyamine, the filter run time was decreased to less than 20 hours when the number of *Synedra* in the filtration inflow water increased to over 200 cells/mL. However, when polyamine was added, it was possible to maintain the filter run time for more than 20 hours with an inflow of 500 cells/mL of *Synedra*, and it was even found possible to maintain a run time of more than 20 hours at approximately 1,000 cells/mL using the correlation equation. Relation between number of *Synedra* population of filtration inflow water and filter run time with the addition of polyamine is shown in Fig 9.

As shown in Table 4, the average efficiency in the removal of *Synedra* in B water treatment plant was 56% when the coagulant (PACS2) was injected. However, when polyamine was injected in addition to the coagulant, the average removal efficiency of *Synedra* was increased to

79%, and the average removal efficiency of *Synedra* was 90%

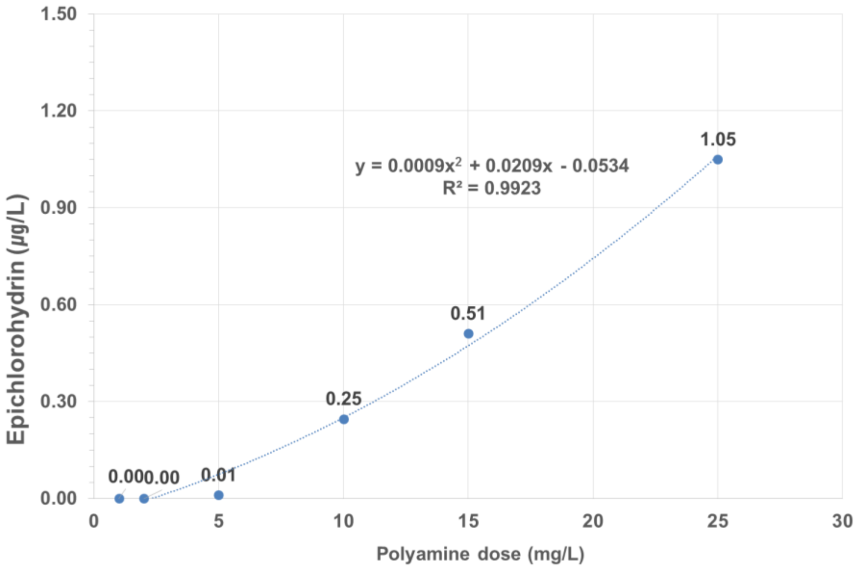



Fig. 7 Experimental results on residual epichlorohydrin concentration by polyamine injection rate

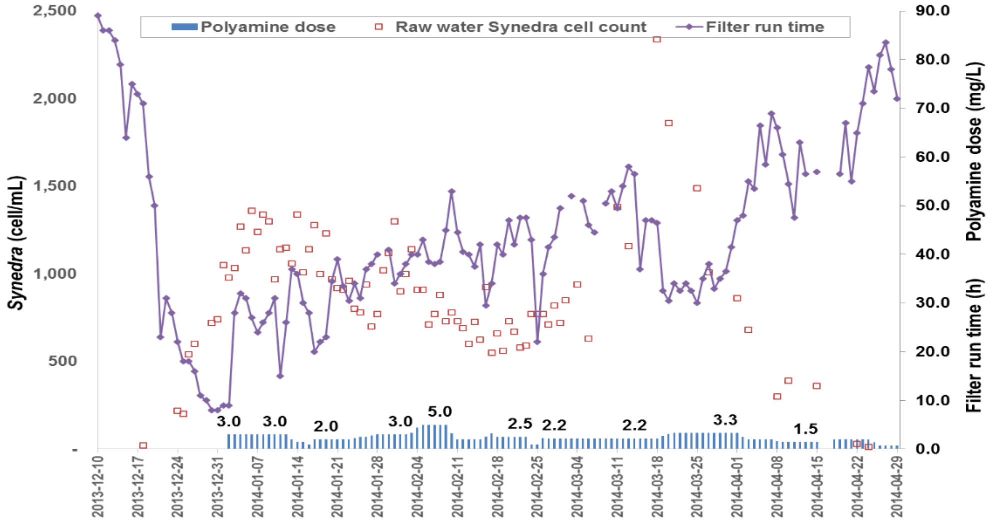



Fig. 8 Relation between number of *Synedra* population in raw water, polyamine injection rate, and filter run time in G water treatment plant

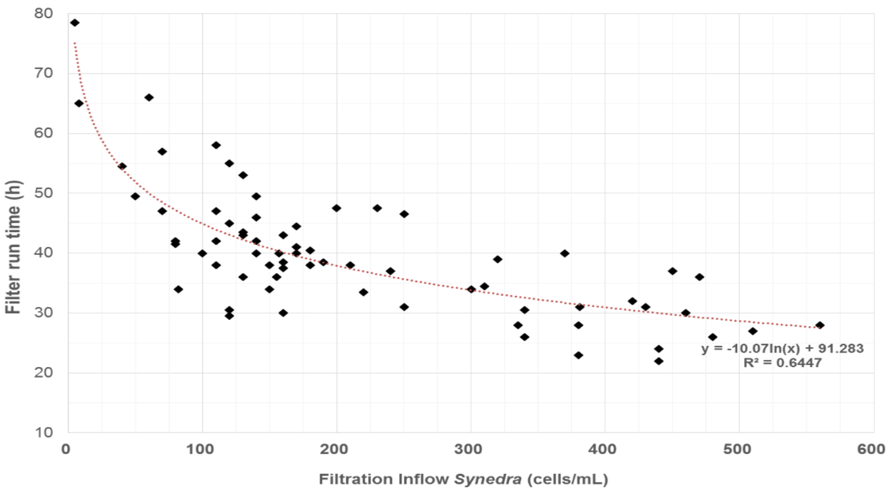
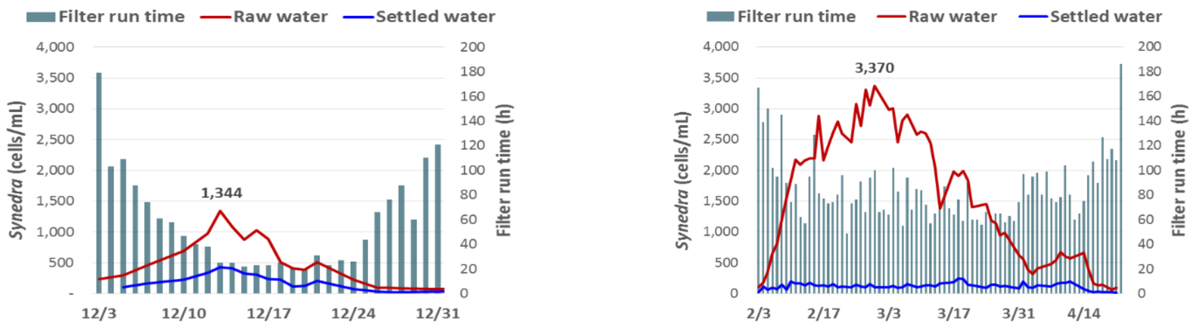



Fig. 9 Relation between number of *Synedra* population of filtration inflow water and filter run time (G water treatment plant)




(a) 2012 year (b) 2014 year

Fig. 10 Comparison of water treatment operation status in 2012 year and 2014 year(B water treatment plant)

Table 4 Status of *Synedra* removal efficiency by each treatment process in B water treatment plant (2014 year)

| Water Treatment Process | *Synedra* Removal Efficiency (%) | Mean *Synedra* Cells in raw water |
|---|---|---|
| chlorine 3ppm(pre-chlorination) + coagulant 20-25ppm | 56 | 75 cells/mL (2014.1.10.-2014.2.4.) |
| add polyamine 3ppm | 79 | |
| add ozone 3ppm(pre-ozonation) | 90 | |
| add ozone 2-3ppm(pre-ozonation) + polyamine 1-3ppm | 95 | 2,259 cells/mL (2014.2.7.-2014.3.26.) |

when ozone was added, which was approximately 34% higher than the average removal efficiency by coagulant alone. In addition, the average removal of *Synedra* through the addition of ozone and polyamine was 95%, approximately 5% higher than the average removal efficiency by ozone alone.

A comparison of the response that consisted of only the addition of coagulant in 2012 when large amounts of *Synedra* flowed into the B water treatment plant, and the corresponding results obtained through the injection of ozone and polyamine in 2014 can be seen in Fig. 10. It is apparent that the average removal efficiency of *Synedra* from the settled water in 2012 was 65%, compared to 95% in 2014 when both ozone and polyamine were added.

With regards to filter run time, when the *Synedra* population increased in the settled water the filter run time tended to decrease proportionately with the number of *Synedra* increased in the raw water, to approximately 20 hours. Under the application of ozone and polyamine, the *Synedra* population in the settled water remained stable at below 200 cells/mL and the filter run time was maintained at 50 hours or more even when the number of *Synedra* in the raw water increased to a maximum of 3,370 cells/mL.

Other factors as well as the number of *Synedra* population can also inhibit filtering. Upon reviewing data from the operation of multiple water treatment plants receiving raw water from the Paldang water source, it became apparent that the size of the individual *Synedra*, which was dependent on the species, also had a significant effect on filter clogging.

In 2018, an increase in the population of *Synedra* occurred in the Paldang water source of the Han river basin. As shown in Table 5, when the number of the *Synedra* population increased to a maximum of 6,890 cells/mL in April–May, the filter run time did not decrease significantly in the water treatment plants receiving raw water from the Paldang water source. However, at the beginning of June, filter run time was reduced to approximately 30 hours, even though it was apparent that the number of *Synedra* present in the water was less than at the end of April.

As seen in Fig. 11, the size of the individual *Synedra* was 100-200 ㎛ in April, but at the beginning of June the number of *Synedra* with a size of 250 ㎛ or more had increased by 90% or more, and the filter run time decreased drastically (with a correlation coefficient of $R^2$=0.7191). According to these results, the size of *Synedra* is also considered to be a factor that greatly influences filter clogging. Therefore it is necessary to take measures to cope with the optimum water treatment considering both of these factors.

## 4. Conclusion

This study evaluated the characteristics of water treatment and the efficiency of the removal via each treatment process used to mitigate filter clogging by the algae *Synedra*. In this study, data from the actual operations used in the water treatment plants were analyzed to determine the optimum method of treatment in the removal of large numbers of *Synedra* from the water treatment plant. The following conclusions were obtained:

- Chlorine injection can increase the removal of *Synedra*, but the effect of increasing the injection rate was not found to be significant. Ozone increased the removal efficiency of *Synedra* as the injection rate increased, and removal of 80% or more of the algae was achieved after the addition of more than 2 mg/L.

Table 5 The status(population and size) of *Synedra* occurrence in Paldang water source and the mean filter run time at the nine water treatment plants receiving raw water from the Paldang water source (analysis of K-water monitoring data)

| Date (2018 year) | 4.23 | 5.8 | 5.18 | 5.21 | 5.23 | 6.7 | 6.8 | 6.9 | 6.10 |
|---|---|---|---|---|---|---|---|---|---|
| *Synedra* population (cells/mL) | 6,890 | 3,109 | 1,307 | 238 | 317 | 57 | 594 | 1,470 | 1,960 |
| *Percentage of Synedra* of size 〉250 μm (%) | 0 | 0 | 0 | 0 | 0 | 38 | 63 | 90 | 94 |
| Filter run time (h) | 60 | 73 | 70 | 72 | 65 | 65 | 63 | 48 | 35 |

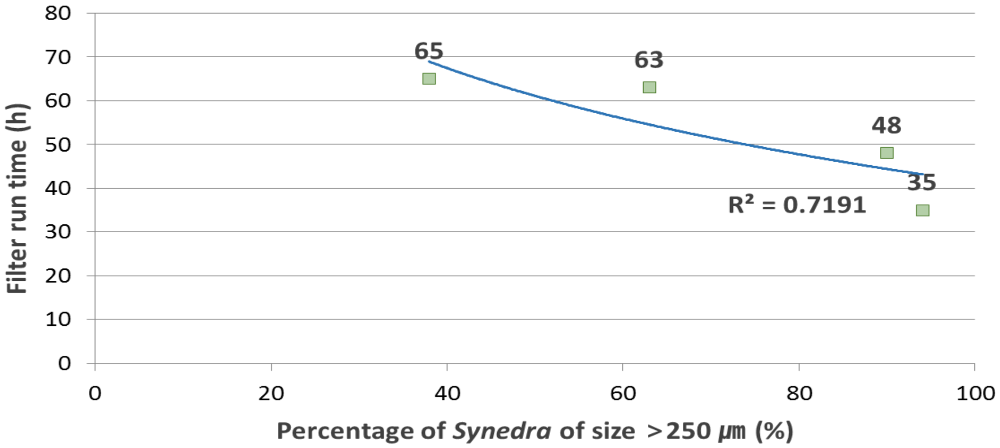



Fig. 11 Reduction status of Filter run time according to *Synedra* size 250 μm or more Ratio

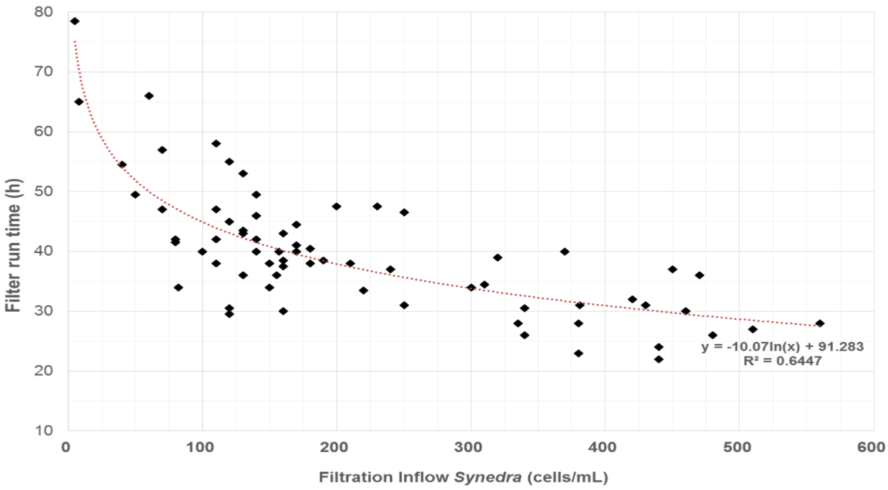



Fig. 9 Relation between number of *Synedra* population of filtration inflow water and filter run time (G water treatment plant)

- More *Synedra* were removed when PAHCS (Poly Aluminum Hydroxy Chloro Sulfate, $Al_{13}(OH)_{28}Cl_{9}SO_4$)) addition was increased, and a removal efficiency of 20–30% was shown in the normal range (20–40 mg/L) of the injection of the coagulant.
- The injection of polyamine, a coagulant aid, increased the effect o
- f crosslinking, and the floc became almost spherical, which increased the settling velocity and the *Synedra* removal efficiency to more than 80%.
- As a result of the water treatment in plant G, the filter run time decreased to 10 hours or less when coagulant was injected alone, but increased to 40 hours after polyamine (3 mg/L) was also injected. The filter run time was subsequently maintained for more than 20 hours even when the *Synedra* population increased to 2,340 cells/mL.
- In water treatment plant B, the average removal of *Synedra* was 56% when the coagulant was injected alone, and the filter run time decreased rapidly with an increase in the number of *Synedra* in the raw water. However, the average *Synedra* removal efficiency increased to 79% after the addition of polyamine, 90% for ozone injection, and 95% for "ozone + polyamine" injection, after which the filter run time was maintained steadily for more than 50 hours.
- The average filter run time was maintained at 60 hours when the *Synedra* population increased to 6,890

cells/mL in Paldang water source. but when the ratio of *Synedra* of at least 250 ㎛ in length increased by 38% to 94%, the filter run time decreased rapidly from 65 hours to 35 hours. Therefore, it is apparent that the size of *Synedra* also has a significant effect on the filter run time.

## 5. Acknowledgements

We thank the process manager of each water treatment plant and the researchers at the K-water Institute for providing laboratory analysis data and actual process operation data for this research.

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