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Control of assimilable organic carbon (AOC) concentrations in a water distribution system

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ABSTRACT

The aim of this study is to measure the bioavailable organic matter content in water. This study examines the changes in assimilable organic carbon (AOC) concentrations in a traditional water treatment plant in southern Taiwan and its associate water distribution system. The addition of chlorine to raw water is shown to produce an increase in AOC, resulting in waterborne AOC concentrations in excess of 50 μg acetate-C/L in some circumstances. Examination of water distribution networks indicate that AOC values decrease as the distance from the treatment facility increases. The residual chlorine concentrations in the distribution system must be in the range from 0.52 to 0.73 mg/L.

Keywords: Assimilable organic carbon (AOC); Water treatment plant; Distribution system

1. Introduction

In recent years, the sources of drinking water in Taiwan have been polluted by organic matter, increasing the difficulty of treating the water and worsening the quality of treated water. The literature has suggested that the worsening of water quality in water distribution networks may be the result of outside pollutants (as in the cases of damaged water pipes) as well as the proliferation of microorganisms in the pipes themselves. The latter may be referred to as after-growth or regrowth phenomena [1]. As Taiwan is located in a low-latitude region, the warm and humid climate facilitates the growth of microorganisms. The proliferation of microorganisms negatively affects water distribution systems and water quality by accelerating the corrosion of pipelines and causing problems such as unpleasant odors and discoloration resulting from the metabolic products of microorganisms or biofilms [2].

Currently, chlorine is typically added during the treatment process to prevent the growth of microorganisms. The use of chlorine as a treatment agent requires the maintenance of a certain concentration to control the growth of microorganisms. However, excessive levels of chlorine tend to have negative consequences for taste and potability; chlorine can also produce by-products such as trihalomethanes. To correct these issues, changes in the treatment methods, regular fishing of pipelines, changes in the pipeline materials, and control of corrosion are all necessary [3]. On the preventative side, the most effective method for addressing this issue is to limit the nutrients that are required by waterborne microorganisms [4].

Assimilable organic carbon (AOC) values reported for treated water in the USA ranged from about 20 to

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more than 400 μg acetate-C/L, with median values of about 100 μg acetate-C/L [5]. In Japan, it was reported that the AOC in finished water ranged from 50 to more than 150 μg acetate-C/L [6]. These values are much higher than those observed in the ranges from 1.1 to 57 μg acetate-C/L in the Netherlands [7].

AOC values are used as a metric for controlling the growth of *Escherichia coli*. Studies have shown that when AOC is maintained below 10 μg acetate-C/L, the addition of chlorine is not necessary to control the growth of heterotrophic bacteria; the growth of heterotrophic bacteria may occur from 15 to 50 μg acetate-C/L, and the growth will definitely occur at levels above 50 μg acetate-C/L. These results clearly demonstrate the importance of AOC in controlling the growth of microorganisms.

This study examined the post-treatment water quality parameters in the water distribution pipelines as well as in the reduction in and changes in AOC concentration. This distribution network selected for this study received water from a conventional water treatment plant located in Taiwan.

2. Experiment and research methods

2.1. Water sample collection and transportation

Samples were collected from December 2009 to November 2010 at various points during the treatment process. Fig. 1 shows the major treatment processes of the Chia-yi Water Treatment Plant (CYWTP). Sampling was conducted once per month, and 12 samples were collected at each sampling event as shown in Fig. 1. The CYWTP is located in the north of Changzhu village, Chia-yi City, Taiwan. The volume of its water supply is treated around 100,000 m^3/day of water, and its water source is the Bazhang River region. The water is channeled through the Ren-Yi-Tan Reservoir and the Lan-tan Reservoir and is treated by the processes such as the Pulsatube process, rapid filtering, and chlorination. This water is then provided to various areas such as Chia-yi City, Minxiong Township, Xingang Township, Beigang Village in Yunlin County, and Baihe Township in Tainan County in south Taiwan. Table 1 presents the operation parameters for CYWTP [8].

2.2. Water quality analysis

In addition to AOC, the water quality analysis in this study also examined other indicators of water quality, including pH, water temperature, conductivity, total volume of dissolved solids, free effective chlorine, UV_{254}, ammonia, nitrate nitrogen, total organic carbon (TOC), dissolved organic carbon (DOC), coliform bacteria, and total bacteria count, constituting a total of 13 indicators.

2.2.1. Measuring TOC and DOC

A wet oxidation TOC analyzer (O.I. Analytical Aurora 1030) was used for TOC and DOC testing. Ultra-pure water was used in the experimental process to reduce interference and increase accuracy. Measurements were made using an nondispersive infrared detector to analyze TOC. For the analysis of DOC, the water samples were first filtered through a 0.45-μm filter paper and then subsequently injected into the TOC analyzer to measure the concentration. The DOC that is determined using this method is also known as non-purgeable dissolved organic carbon.

2.2.2. Measuring the quantity of UV_{254} and SUVA

The water sample was filtered through a 0.45-μm filter paper, to remove the suspended particles in the raw water. The sample was then placed into a 1-cm optical path quartz tube and placed inside a spectro-

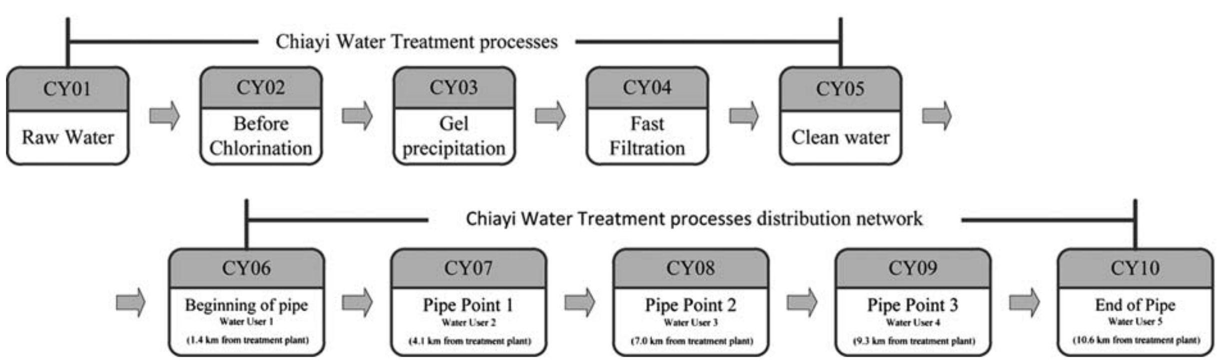

Fig. 1. Sampling points in the water treatment unit process and distribution pipeline as well as associated codes.

Table 1
Operation parameters for the CYWTP [9]

Unit	Operation parameters
Coagulation–sedimentation	Hydraulic retention time: 60 min
	Surface loading: 88 m^3/m^2-day
	Surface velocity: 4.25 cm/min
Rapid filter	Surface area: 100 m^2
	Filter rate: 250 m/day
	Depth of media: 39 cm
Clean water	Flow rate: 90,000–120,000 m^3/day

photometer to measure the absorption. The measurement was performed as follows. Ultraviolet rays with a wavelength of 254 nm at room temperature were used in the measurement. Because organic substances with ring-shaped bonds and double covalent bonds absorb UV rays, the measured absorption values can be used to evaluate the amount of organic matter in the water. The unit of UV_{254} measurement was cm^{-1}.

SUVA is calculated by dividing the UV_{254} by the DOC concentration (UV_{254}/DOC). The SUVA content and the concentration of aromatic carbons are strongly correlated with each other. Therefore, they can be used as indicators of the contents of both organic matter and unsaturated organic compounds in the water sample.

2.2.3. Measuring the concentration of NH_3-N

For this method, 1.0 mL of phenol solution, 1.0 mL of sodium nitroprusside, and 2.50 mL of oxidizing solution were added to a 25.0-mL water sample. The solution was mixed in a 50-mL reaction flask, and the reaction proceeded in the dark for 1 h. Following color development, the solution was placed in a spectrophotometer with a fixed wavelength of 640 nm to measure the absorption.

The water sample was filtered through a 0.45-μm filter paper and then injected into an ion chromatographic instrument (Metrohm 861 advanced compact IC). The principle is that as the affinity between the eluent in the ion chromatography tube and the anion exchange resin changes, the water sample dissociates. The concentration was determined using a conductivity detector.

2.2.4. AOC measurement

The method for AOC measurement used herein the method of Van der Kooij. In this approach, two strains of bacteria, *Pseudomonas fluorescens* strain P17 (ATCC 49642, AOC_{P17}) and *Spirillum species* strain NOX (ATCC 49643, AOC_{NOX}), were used in biometric testing. First, the water sample was sterilized at 70℃ for 40 min. After the sample had been cooled to room temperature, AOC_{P17} and AOC_{NOX} were added; the solution was then cultivated at 25℃ for 8 days. The culture medium was Lab-Lemco Nutrient Agar. On the 1st, 3rd, 5th, 7th, and 8th days of cultivation, samples were extracted and daubed on the medium for the bacterial colony analysis, until the maximum number of colonies was reached. The AOC concentration was calculated. The unit of measurement was μg acetate-C/L [9,10].

3. Results and discussion

3.1. Water quality summary

Table 2 presents the water quality parameters for raw water, treated water, the head of the pipeline, and the end of the pipeline. Ammonia levels, coliform bacteria count, and total bacteria count were partially reduced by the treatment. UV_{254} and SUVA levels were lower in the treated water than in the raw water, evidencing the fact that the addition of chlorine at the beginning and end of the treatment process destroyed covalent double bonds and organic bonding rings, reducing the UV_{254} levels. A proportional increase in small organic molecules was associated with a reduction of SUVA. DOC levels were similar in raw water and treated water, while AOC_{NOX} levels were significantly higher in treated water. Traditional water treatment processes primarily remove the organic matter using particles or gel; the addition of chlorine converts waterborne organic matter into hydrophilic organic molecules, reducing the efficacy of DOC removal. As the addition of chlorine leads to the formation of AOC_{NOX} using matter and the subsequent treatment is somewhat ineffective in removing this type of matter, AOC_{NOX} levels substantially increased.

The biological stability of distribution pipelines is based on the analysis of AOC. According to the literature, AOC indicates the presence of organic matter that is most easily used by the microorganisms. Changes to AOC in distribution pipelines are primarily caused by the addition of disinfectant and the regrowth of heterotrophic bacteria. The impact of disinfectant on AOC cannot be accurately characterized by linear growth or reduction; biodegradability must also be considered. The proliferation of heterotrophic bacteria in drinking water could somehow be stimulated during the transportation process, and therefore, it may most appropriately represent the biological

Table 2
Comparison of the average water quality parameters in the CYWTP and the distribution network from December 2009 to November 2010

	Cl	DOC	UV_{254}	SUVA	NH_3–N	AOC			Coliform bacteria	Total bacteria count
						AOC_{P17}	AOC_{NOX}	AOC_{Total}		
Unit	mg/L	mg/L	cm^{-1}	L/mg-m	mg/L	µg acetate-C/L			CFU/100 mL	CFU/mL
Raw water	–	1.108	0.024	2.166	0.059	95.43	10.77	106.21	61	588
Treated water	0.73	1.013	0.014	1.382	0.023	44.08	24.94	69.02	<1	<1
Head of pipeline	0.65	1.079	0.014	1.297	0.023	41.70	30.41	72.11	<1	<1
End of pipeline	0.52	1.045	0.017	1.627	0.018	40.51	24.14	64.65	<1	4

stability in the distribution pipeline. Annual average AOC levels in treated water were approximately 69 µg acetate-C/L, falling short of the levels necessary, as asserted by Van der Kooij, to control the growth of heterotrophic bacteria; for such control, AOC levels must be below the standard of 50 µg acetate-C/L.

In addition to the changes in the conditions described above (reductions in chlorine and AOC levels; the necessary residual chlorine concentrations range for control is 0.52–0.73 mg/L), the SUVA levels appeared to rise, indicating that the proportion of hydrophilic molecules dropped. AOC_{NOX} bacteria tend to use this type of organic matter, so this thus explains the drop in AOC_{NOX}. With the reduction of AOC, the coliform bacteria and total bacteria counts rose slightly but remained within the water quality standards. However, the reduction of AOC suggests that it had been consumed by heterotrophic bacteria, evidencing the growth of heterotrophic bacteria. While this study defined the pipeline distance as from the head of the pipeline to the end of the pipeline, the end of the pipeline was utilized for measurements to water from other water treatment plants. The end of the pipeline in this study was not actually the terminal end of the pipeline. It is therefore possible that microorganism growth at the actual terminal end of the pipeline could be worse than at the end of the pipeline defined in this study. The growth of microorganisms may also lead to problems such as unpleasant odors or discoloration. To prevent these problems, AOC concentrations in treated water must be reduced, which means that water treatment plants must provide better quality water. Therefore, the processing of AOC in treatment plants is a crucial topic.

3.2. Micropollutant variations in the CYWTP distribution network

Fig. 2 shows the average AOC levels in the distribution pipeline during the research period. After entering the pipeline, AOC levels evidently increased very slightly. The sodium chlorate added at the water treatment point could possibly interact with organic matter in the water to form an organic matter more easily used by organisms, thereby increasing the AOC levels. AOC levels decreased toward the end of the pipeline as the distance from the source increased; it is possible that concentrations of chlorine are reduced as the distance increases, limiting the ability of the chlorine to control the bacterial growth. The resulting proliferation of microorganisms could reduce the concentration of AOC.

Studies by LeChevallier et al. [11] and Colbourne et al. [12] found that heterotrophic bacteria proliferate

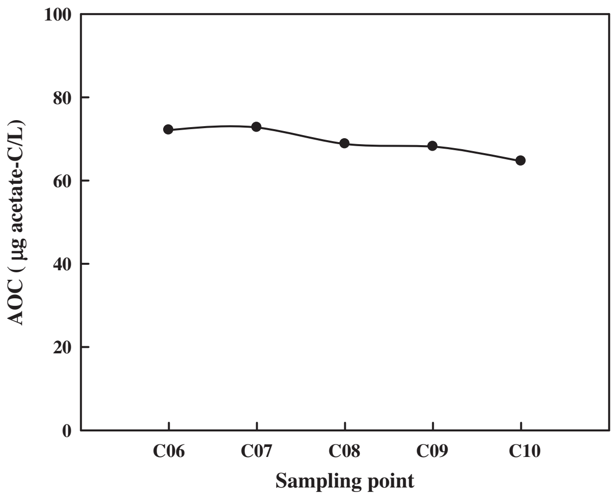

Fig. 2. Changes in the average annual AOC levels in the distribution pipelines.

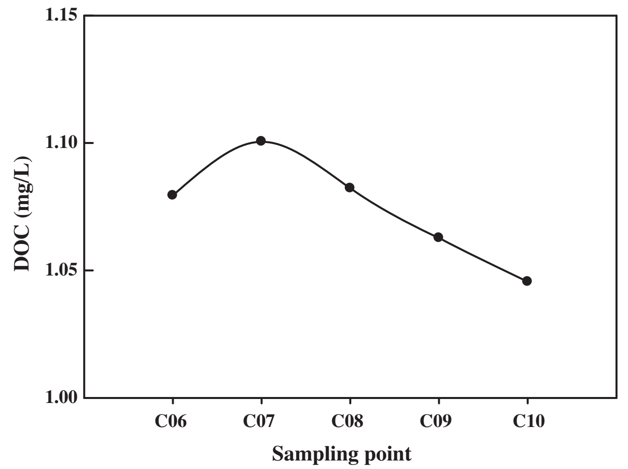

Fig. 3. Changes in the average annual DOC levels in the distribution pipelines.

in the biofilms within pipelines regardless of whether disinfectant is added [11]. AOC concentrations are also reduced, possibly because the growth of bacteria in the biofilm on the pipe walls reduces AOC. However, some matter escapes from the biofilm, increases waterborne AOC and the total bacteria count [4,7].

However, the results of the total bacteria count and coliform bacteria testing revealed no significant growth. Testing of the total bacteria and coliform bacteria counts involves the measurement of floating bacteria, excluding the biofilms adhering to the pipe walls. International studies indicate that the regrowth phenomena in distribution pipelines include both the floating bacteria and the biofilms on pipe walls. Therefore, reductions in AOC concentration could result from the biofilm extracting AOC from the water. Fig. 3 shows the changes in the DOC levels in the distribution pipelines, indicating that the DOC levels are initially high but later decline; this trend is consistent with that of the AOC levels.

3.3. Equations relating AOC and DOC in the CYWTP distribution network

Fig. 4 shows the relationship between DOC and AOC in the distribution pipeline; a strong association between the two is apparent, while there is no significant association between DOC and AOC in the water treatment plant. This difference may result from the use of chemical or physical processing methods in traditional water treatment. Aside from removing the organic matter most readily utilized by several organisms, traditional treatment also removes organic matter that is difficult or impossible for organisms to use. As a result, the removal of DOC does not accurately reflect the amount of AOC removal. Microorganisms and biofilms in pipelines consume DOC; AOC is a portion of DOC, so a reduction in DOC levels also represents a reduction in AOC levels. Consequently, DOC and AOC are more strongly associated in the distribution pipelines.

This study used DOC as a replacement index for AOC. Because the study revealed that testing methods for AOC can be complicated and time-consuming, establishing a predictive model would reduce the time needed to estimate AOC. This paper divided AOC into concentrations of DOC for the correlation analysis. A graph of the regression results is shown in Fig. 4. The R values in these R^2 values of this regression is 0.8205. The correlation results indicate that

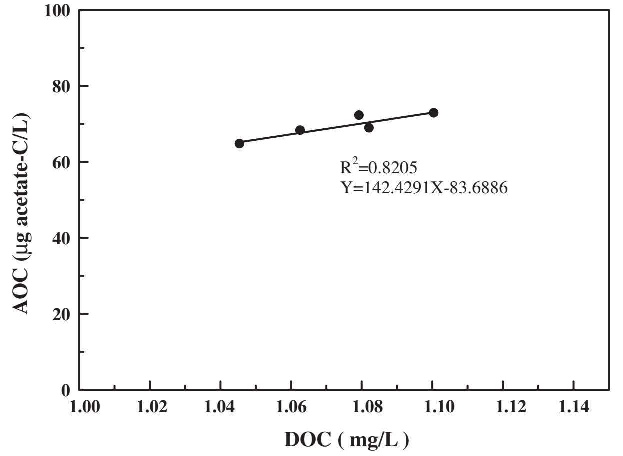

Fig. 4. The association between average DOC and average AOC values in the distribution pipelines.

AOC was highly correlated when the DOC concentration was between 1.0 and 1.2 mg/L in the distribution pipeline. Eq. (1) is the correlation equation for AOC to DOC.

The actual relationship between DOC and AOC might not be truly reflected in this study due to the limited data collected. Long-term monitoring and analysis may therefore be required to more confidently understand the true degree of the relationship between DOC and AOC. Additional actions would establish a complete database to serve as the next step for controlling and predicting the disinfection by-products in water treatment plants.

$$AOC = 142.4291\ (DOC) - 83.6886 \quad (1)$$

4. Conclusion

Reducing AOC levels can prevent the growth of microorganisms in the distribution pipelines. Preventing the growth of heterotrophic bacteria requires a reduction in the AOC levels below 50 μg acetate-C/L and control of chlorine dosage in the post-chlorination unit. Here, however, AOC levels at some sampling points in the treated water exceeded the 50 μg acetate-C/L level. Traditional treatment processes might have limited effectiveness when used to treat lower-quality raw water.

A correlation analysis of the water quality concentrations of AOC and DOC resulted in an R^2 value of 0.8205 when the DOC concentration in the distribution pipeline ranged from 1.0 to 1.2 mg/L. These values indicate a high level of correlation. In the future, long-term monitoring and analysis may be required to establish a complete database of results. This database could be helpful in investigating and analyzing the relationship between each compound and could serve as a basis for water purification plants to better control and decrease pollutant concentrations during the purification process.

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