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Reproduction of *Staurastrum* sp. within a water treatment plant caused by the recycle of combined sludge water and backwash water: a field investigation

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ABSTRACT

It is well known that the recycle of sludge water and filter backwash water in drinking water treatment plants (WTP) may cause water quality problems including suspended solids, pathogenic protozoans, dissolved organic matters, and disinfection by-products. However, it is still uncertain whether the recycle process can cause algal problems in a WTP with algal-laden raw water. A field survey was performed in a WTP, located in Tianjin, China, to investigate the variation of algal species and density during the treatment and recycle process. The results showed *Staurastrum* sp., a non-dominant species in raw water, regrew and became the unique dominant species in the combined sludge tank (CST). The reproduction of *Staurastrum* sp. increased the treatment loading, clogged the filter, and deteriorated the quality of finished water. Bench-scale experiments indicated chlorination was inefficient to inactive *Staurastrum* sp., which resulted in that living cells of this alga can enter into the CST. Culture experiments indicated *Staurastrum* sp. favors a moderate concentration of Fe (0.6–2.0 mg/L) and grows slowly under a low concentration (0.1 mg/L). Thus, the high concentration of Fe (0.6 mg/L) originated from the residual coagulant facilitated the reproduction of this alga in the CST. Cutting off the recycle pathway and destroying the favorable growing conditions in the CST may be feasible methods to control the reproduction of *Staurastrum* sp. in the WTP. This study showed the recycle of sludge water and filter backwash water can cause algal problems in WTPs, which should be an important issue for drinking water treatment researchers and engineers.

Keywords: *Staurastrum* sp.; Drinking water treatment; Sludge water; Filter backwash water; Algal reproduction

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1. Introduction

Conventional drinking water treatment plants (WTP) produce plenty of liquid waste residual during the daily works. Most of the water comes from sedimentation basins (sludge water) and rapid filters (backwash water), and can be up to 10% of the plant production [1]. Due to the large volume of the liquid residual, it is important and valuable to recycle these water streams for the water resource conservation. However, because of the high concentrated impurities in the recycle water (suspended solids, residual coagulants, and organics) [2,3], the safety of water reuse has been seriously concerned by researchers and engineers.

It seems that the recycle of sludge water and backwash water in a WTP does not worsen the quality of finished water or the adverse effects are negligible. The sludge water and backwash water contains plenty of destabilized particles which can provide additional collision sites and enhance the performance of coagulation [4,5]. Thus, the recycle do increase the turbidity and the pathogenic protozoan concentration in raw water, but most of these contaminants can be well treated by conventional water treatment processes [4–7]. For the same reason, the recycle can also enhance the removal of natural organic matter (NOM) under a neutral condition [8], but the concentration of NOM in the finished water may increase moderately at pH 8.5 [7]. Researchers also indicate that there is a higher disinfection by-products (DBPs) formation potential in the backwash water than that in raw water, but mass balance calculations demonstrate that the recycle process does not impact DBP concentration in the mixture significantly [9]. Overall, the recycle of sludge water and backwash water would not cause a security problem if the treatment processes are well operated, though the chemical demands and the backwash frequency may increase [2,5,6,8].

However, it is rarely reported the impacts of recycle process on the effluent quality of WTPs with algal-laden raw water. Excessive algae in raw water can lead to high turbidity [10], cause taste and odor problems [11,12], and produce various algal toxins such as microcystins, cylindrospermopsins, and nodularins [13]. In WTPs, algae can increase coagulant and oxidant demands, short filter runs, generate DPBs during the disinfection process, and cause microbial regrowth in distribution systems [14,15]. Since most of algal cells are removed by coagulation–sedimentation and filtration, it can be inferred that these removed algal cells can go back into the treatment systems with the recycled streams, which may interrupt the operation of treatment processes. Thus, it is necessary to investigate the transfer of algal cells and assess the security of finished water during the recycle process in WTPs with algal-laden raw water.

In this study, a field survey was conducted to investigate the variation of algal densities in different treatment units of a conventional WTP that employed a recycle procedure of sludge water and backwash water. Several bench-scale experiments were performed to explain why some species of algae can grow within the WTP and become a dominant species. The results implied that the risk of algal reproductions in WTPs should be considered when the sludge water and backwash water are reused without a proper regulation.

2. Materials and methods

2.1. WTP description and sampling sites

The surveys were conducted in the summer of 2007 in a WTP located in Tianjin, China. Water samples from the main treatment units were collected and analyzed in the early July, the late July, and the mid-August. For each period, surveys were conducted for four consecutive days. The arithmetic means were obtained (±SD) and used as the final values. The samples from the recycle system were collected on 4 July and 4 August, respectively. The algal densities of

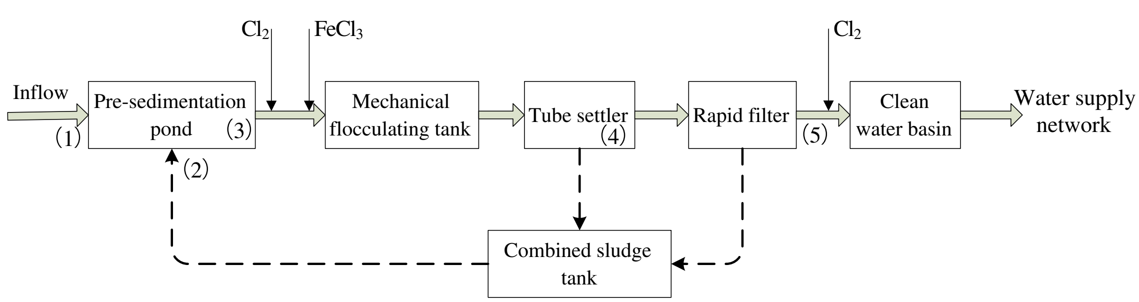

Fig. 1. The sketch of the treatment and the recycle processes. The numbers represented sampling sites.

sludge water and backwash water decreased significantly with the increased sludge discharging and backwashing period. Thus, the samples of the sludge water and the backwash water were collected from the initial water streams (0.5–1.5 min) to measure the maximum algal densities of the discharged water.

The treatment processes were shown in Fig. 1, and the number in the figure represented the sampling sites. The water production was 10,000 m^3/d. The raw water came from the Yuqiao reservoir, which is the main water source for Tianjin. The water is characterized by high algal densities from July to September, and the value can be as high as 7×10^4 cells/mL. Approximately, 10,000 silver carps were fed in the pre-sedimentation pond (PSP) to reduce algal densities in raw water. The sludge water and backwash water were discharged into the combined sludge tank (CST), and then they were mixed with the raw water in the middle of the PSP and were retreated by the following processes as shown in Fig. 1. The hydraulic retention time (HRT) of the PSP and the CST were approximately 120 and 12 h, respectively.

2.2. Analytical method

Algal cells in water samples were counted by the method described by Ma et al. [16]. In brief, water samples were prepared by filtration enrichment, dispersed by ultrasonic vibration, and then phytoplankton species were identified and measured by a microscope (Olympus BX41, Tokyo, Japan).

Algal cells adhered to the sand in the filter were counted by the following procedure. The sand at a depth of 0, 0.4, 0.6, and 0.8 m was collected prior to the backwashing procedure. Then, the sand was washed by water for three times. The wash water was combined and the cells in the water were counted by the same method for water samples described above. The cell densities in wash water were converted to adherent cell amounts by calculating the wet weight of sand and the volume of wash water.

Other parameters, including turbidity, temperature, pH, total iron, total phosphorus, ammonia nitrogen, alkalinity, chlorophyll-a (Chl-a), and permanganate index, were measured according to standard methods [17].

2.3. Algal culturing

The culture medium was modified from a standard Knop medium [18]. The final constituents of the medium were 12.5 mg/L KH_2PO_4 (equivalent to 2.85 mg P/L), 12.5 mg/L $MgSO_4 \cdot 7H_2O$, 12.5 mg/L KCl, 50 mg/L $CaNO_3 \cdot 4H_2O$, and ferric ammonium citrate ranged from 0.04 to 5.94 mg Fe/L. The low concentrations of nutrients in the medium were designed to ensure the nutrient concentrations were comparable to those in raw water. Algal cultures collected from the effluent of CST were diluted to approximately 4,000 cells/mL and incubated in six parallel glass containers (0.3 m × 0.3 m × 0.25 m) with a temperature of 25 ± 1℃ and an illumination of 3,300 lx in a 12 h light/12 h dark cycle. Because of the high concentration of Fe in the effluent of CST (approximately 0.6 mg/L), the inoculation also introduced a low amount of Fe (approximately 0.06 mg/L) into the medium and the initial concentrations of Fe in the culture were 0.1–6.0 mg/L.

2.4. Pre-oxidation and coagulation–sedimentation experiments

Algal densities were diluted to 5,000–6,000 cells/mL by deionized water to minimize the background interference from different samples, and then were oxidized by sodium hypochlorite (1, 3, 5 mg/L available chlorine). After a 30-min reaction, bench-scale coagulation–sedimentation experiments were conducted using a standard jar-test unit (ZR2–6, Fuhua Co. Ltd, China) consisting of six 2-L glass jars. Ferric chloride was used as the coagulant. Following the addition of coagulant, samples were subjected to rapid mixing for 30 s at 250 rpm, flocculation for 10 min at 40 rpm, and settling for 15 min. The variations of cell densities and Chl-a were analyzed at the coagulant dosage optimized for turbidity.

3. Results and discussion

3.1. Distributions of algae in the WTP

3.1.1. Distributions in the main treatment units

The variations of algal species and density in the main treatment units were shown in Fig. 2. From July to August, the dominant species in raw water varied from *Chlamydomonas* sp., *Scenedesmus* sp. and *Cyclotella* sp. (in the early July, non-*Microcystis* sp.-dominated period) to *Microcystis* sp. (in the late July and the mid-August, *Microcystis* sp.-dominated period), and the total cell density increased from 2,676 to 53,065 cells/mL. *Staurastrum* sp. was detectable in raw water, but it only accounted for a very small proportion (2.4% in non-*Microcystis* sp.-dominated period and less than 0.3% in *Microcystis* sp.-dominated period). However, the density of *Staurastrum* sp. increased dramatically when the raw water was mixed with the effluent of CST. Compared to the variation of *Microcystis* sp. in raw water, the density of *Staurastrum* sp. in site 2

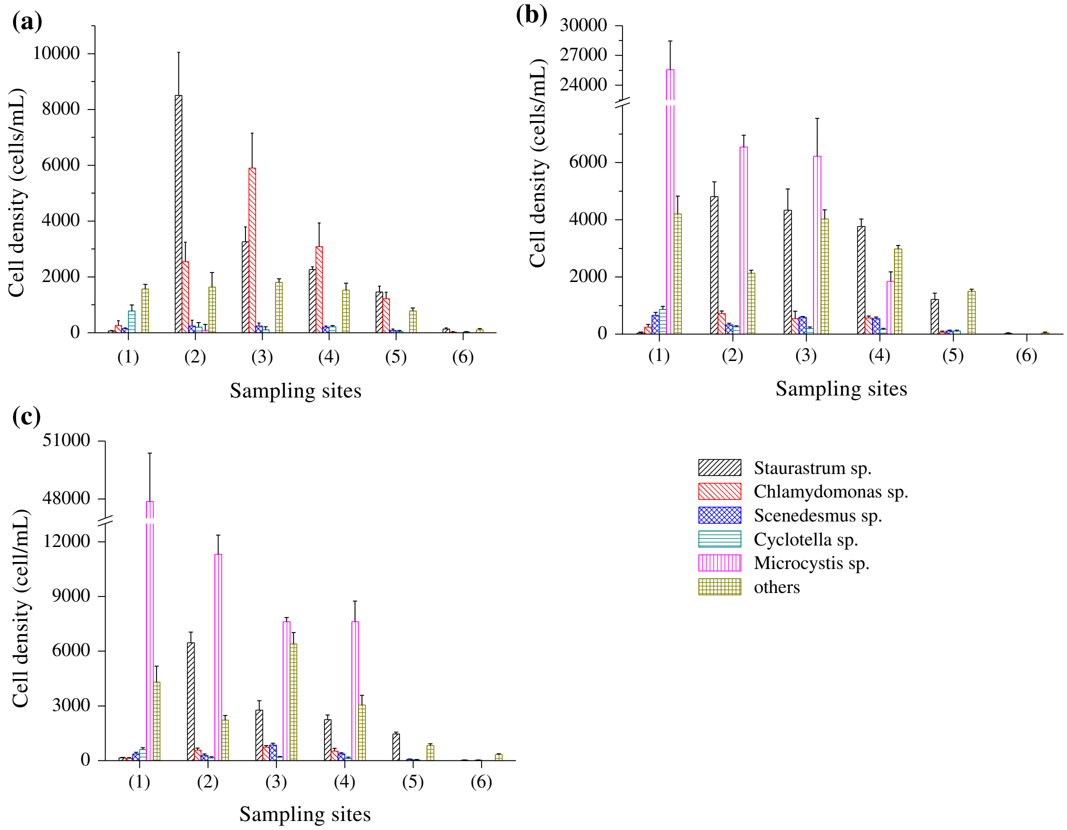

Fig. 2. Variations of cell densities in different treatment units. (1) raw water; (2) raw water blended with the recycle water; (3) effluent of PSP; (4) after pre-chlorination; (5) after sedimentation; and (6) after filtration. (a) sampled in the early July, 2007; (b) sampled in the late July, 2007; and (c) sampled in the mid-August, 2007.

varied insignificantly during the whole summer of 2007 (from 8,500 to 4,809 cells/L). These phenomena imply that *Staurastrum* sp. should come from the CST rather than the raw water. Most of algal cells can be well removed by pre-chlorination, coagulation–sedimentation, and filtration, but the ratio of *Staurastrum* sp. to the total algae increased after sedimentation (from 29.5 to 40.6% in non-*Microcystis* sp.-dominated period and 21.4 to 50.7% in *Microcystis* sp.-dominated period). Moreover, *Staurastrum* sp. was frequently detectable in the filter effluent, which implied that *Staurastrum* sp. deteriorated the quality of finished water.

The variations of algal community structures and densities in the PSP were controlled by the competition among silver carps, zooplankton, and phytoplankton, which have been discussed in our previous studies [16,19]. Silver carps prey on both phytoplankton with large particle size (>10 μm) [20] and zooplankton, which are the predators of phytoplankton with small particle size (<50 μm) [21]. The former effect results in the reduction of algae with large particle size such as *Microcystis* sp., *Staurastrum* sp., and *Cyclotella* sp. in the PSP, while the latter results in the increase of algae with small particle size such as *Chlamydomonas* sp. Thus, the algal structure in the PSP changed from dominant species with large particle sizes to that with small one. This phenomenon has also been reported by other researchers [22,23].

The variations of other physical and chemical indexes, including COD_{Mn}, NH_3-N, P, Fe, and turbidity, along with the treatment process were shown in Fig. 3. The presence of *Staurastrum* sp. did not worsen the water quality obviously from the perspective of physical and chemical indexes, and all the indexes of filtered water could meet the Chinese standard for drinking water quality. However, the leakage of *Staurastrum* sp. from the filter (Fig. 2) increased the disinfection risk and may cause microbial regrowth problem in distribution systems.

3.1.2. Distributions in the water recycle system

The distributions of algae in the filter at different depths were shown in Fig. 4. The surface of the filter

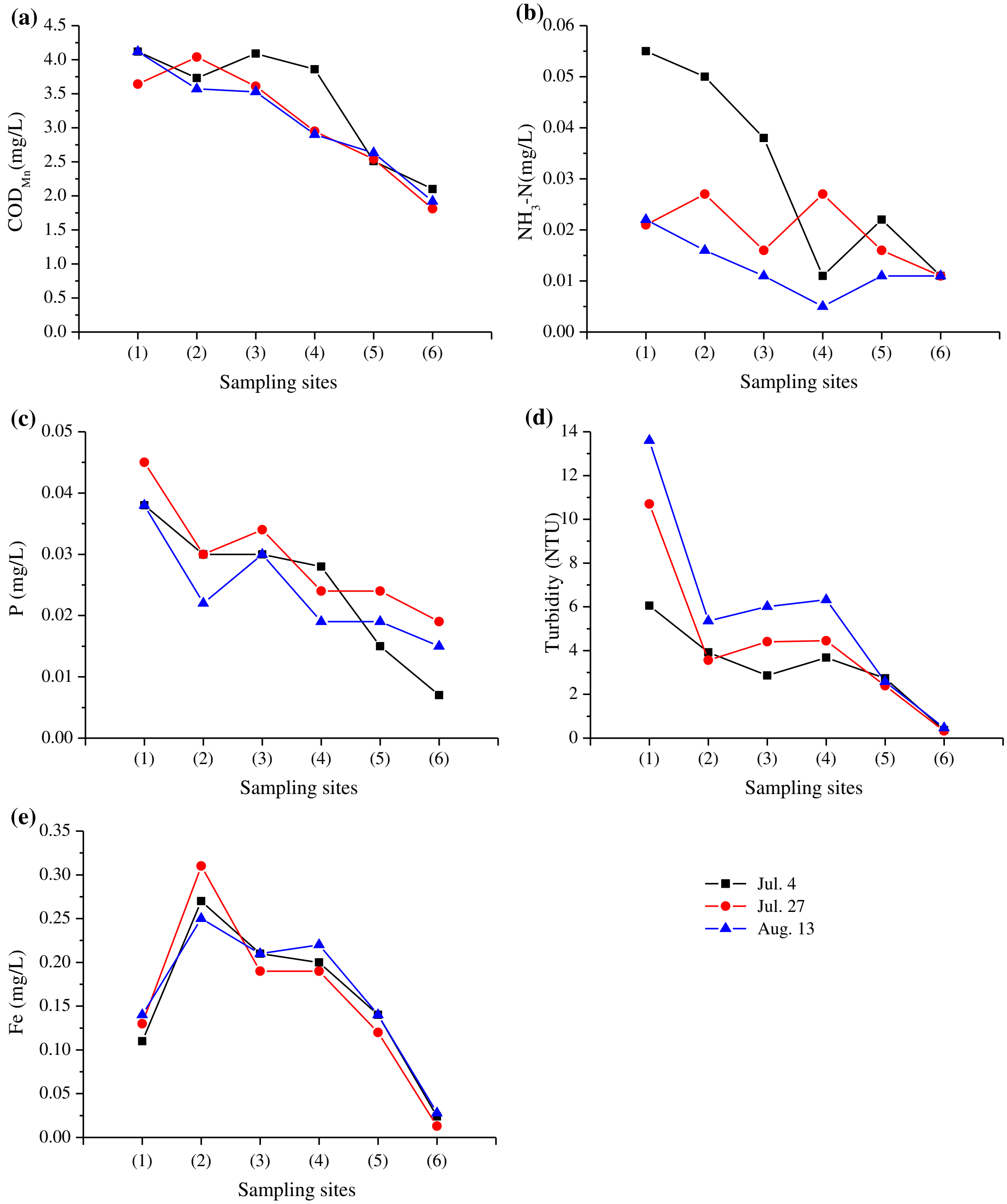

Fig. 3. Variations of CODMn (a), NH_3-N (b), P (c), turbidity (d), and Fe (e) in different treatment units. (1) raw water; (2) raw water blended with the recycle water; (3) effluent of PSP; (4) after pre-chlorination; (5) after sedimentation; and (6) after filtration.

prevented most of algal cells, and the density of adhered cells decreased significantly with the increased filter depth. *Staurastrum* sp. was the dominant species, and the proportions were 74.1–78.8% in non-*Microcystis* sp.-dominated period and 58.5–63.4% in *Microcystis* sp.-dominated period, both of which were much greater than those in the influent of the filter (approximate 41%). This phenomenon implied that *Staurastrum* sp. was easy to be held by the filter but was difficult to be flushed out by the backwash procedure.

Algae in the sludge water and the backwash water were counted and the results were shown in Table 1.

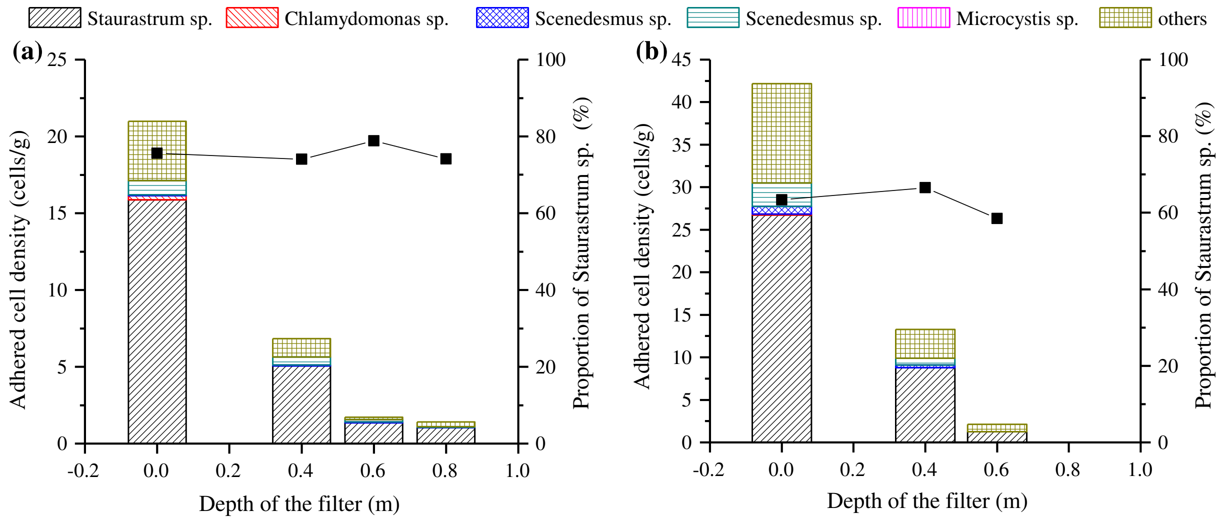

Fig. 4. Adhered algal cells on the sand of the filter. (a) sampling on 4 July, 2007, non-*Microcystis* sp.-dominated period and (b) sampling on 4 August 2007 *Microcystis* sp.-dominated period.

The proportion of *Staurastrum* sp. in the sludge water was slightly smaller than that in the water before coagulation–sedimentation, and the result was in accordance with the fact that the proportion of *Staurastrum* sp. increased after sedimentation. This phenomenon implied that *Staurastrum* sp. was more difficult to be removed by coagulation–sedimentation process than the other species. Previous study [24] indicated that spinal appendages can prevent the cells from close contact. There were four spinal "tentacles" in each cell of *Staurastrum* sp. (Fig. 5). Maybe this was the reason why this alga was more difficult to be removed by coagulation–sedimentation.

The proportion of *Staurastrum* sp. in the backwash water was lower than that of the adhered cells in the filter (but higher than that in the influent of the filter), which confirmed the assumption that backwash procedure cannot flush out the adhered *Staurastrum* sp. effectively. This may also be attributed to the morphological characteristic of *Staurastrum* sp. The surface of this alga is irregular compared with the spherical and the cylindrical species (Fig. 5). Four long and spinal appendages of *Staurastrum* sp. may enhance the adhesion between algal cells and the sand in the filter.

The growth of algae in the CST was also investigated, and the results were shown in Table 2. *Staurastrum* sp. grew rapidly in the tank, and the density in the effluent was 5–7 times larger than that in the influent. The proportion of *Staurastrum* sp. also increased dramatically, and this alga accounted for larger than 90% of the total algal cells in the effluent of the CST. Obviously, the CST was the source of *Staurastrum* sp., and caused the abrupt increase of *Staurastrum* sp. in the PSP as shown in Fig. 2.

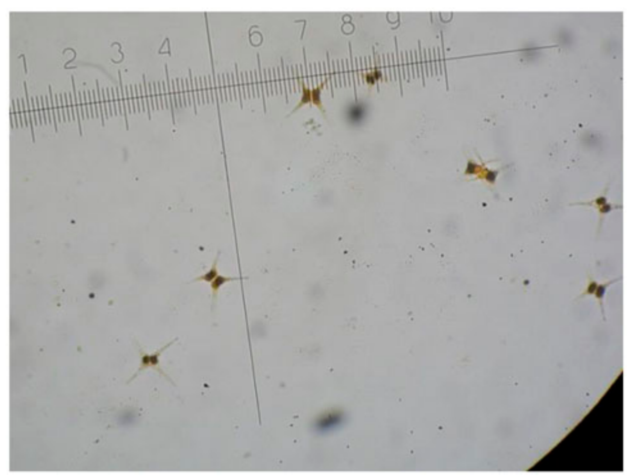

Fig. 5. *Staurastrum* sp. observed via a microscope (×400). Sample was collected from the effluent of the CST.

Since *Staurastrum* sp. is negligible in raw water and accounts for a particularly high proportion in the CST, this alga can be regard as a "natural tracer" which represents the transfer of algae came from the interior of WTP during the water recycle process. In this study, *Staurastrum* sp. regrew in the CST, and re-entered into the treatment system via the recycle of sludge water and backwash water. The reproduction of *Staurastrum* sp. not only increased the loading of WTP, reduced the filtration period (from 24 to 8 h), but also deteriorated the quality of finished water (*Staurastrum* sp. was detectable in the finished water, Fig. 2). Obviously, the recycle of sludge water and backwash water caused the reproduction of algae

Table 1
Algal density in the sludge water and the backwash water

Source	Sampling date	Cell density (cells/mL)		Proportion (%)
		Total	*Staurastrum* sp.	
Sludge water	4 July 2007	34,880	9,200	26.4
	4 August 2007	53,280	5,720	10.7
Backwash water	4 July 2007	53,640	30,470	56.8
	4 August 2007	63,830	29,980	46.9

Table 2
Algal densities in the CST

Sampling date	Water streams	Cell density (cells/mL)		Proportion (%)
		Total	*Staurastrum* sp.	
4 July 2007	Inflow	9,380	6,010	64.1
	Outflow	35,480	33,250	93.7
4 August 2007	Inflow	13,540	5,990	44.2
	Outflow	44,200	42,880	97.0

within the WTP and disturbed the operation of WTP. The characteristic that algae can grow during the recycle process is quite different from other well-studied contaminants such as inorganic particles, organics, and pathogenic protozoan which just accumulate during the recycle process [2,5–8].

3.2. *Reasons for the reproduction of* Staurastrum *sp. in the CST*

Because the reproduction of *Staurastrum* sp. brings many inconveniences to the WTP as discussed in section 3.1, it is necessary to reveal why *Staurastrum* sp. regrew in the CST and became the dominant species. Bench-scale pre-oxidation and coagulation–sedimentation experiment, and algal culture experiment were performed to investigate the causes.

3.2.1. Staurastrum *sp. is difficult to be inactivated by pre-oxidation*

The effluent of PSP was treated by sodium hypochlorite at different dosages, and then was conducted by jar test. The variations of algal densities were shown in Fig. 6. The proportion of *Staurastrum* sp. increased after the treatment, and the results were similar to that shown in Fig. 2. Increasing the dosage of oxidant can enhance the removal efficiency of both *Staurastrum* sp. and the other algal species by coagulation–sedimentation, but the proportion of *Staurastrum* sp. in the settled water still increased from

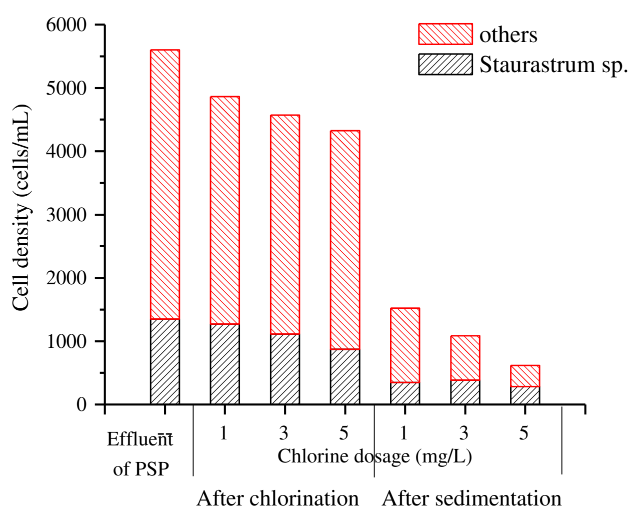

Fig. 6. Variation of algal densities in the effluent of PSP treated by chlorination and coagulation–sedimentation.

23 to 46%. Previous studies [25,26] indicate that oxidation inactivates algal cells and causes the release of intracellular organic matter, which are helpful for the improvement of coagulation. Thus, the phenomenon that the proportion of *Staurastrum* sp. increased with the increase of oxidant dosage after sedimentation implied chlorine oxidation is less effective for the inactivation of *Staurastrum* sp. than the other algal species in the effluent of PSP.

Limited to the experimental conditions in the WTP, cell integrity is not available. Chl-a was analyzed as an alternative index. The variations of Chl-a in the effluent of PSP (mixture of *Staurastrum* sp. and other species) and the effluent of CST (almost pure *Staurastrum* sp. culture) treated by pre-oxidation and coagulation–sedimentation were shown in Fig. 7. The removal rate of Chl-a in the effluent of CST was always lower than that in the effluent of PSP. This phenomenon indicated there were more *Staurastrum* sp. cells survived than the other species after the treatment, and the result was in accordance with the fact shown in Fig. 6. It can be inferred that the survived cells of *Staurastrum* sp. can be retained in the filter and washed back into the CST, and then these cells regrew in the tank and flowed into the main treatment units again with the recycle process.

3.2.2. Moderate concentration of Fe facilitates the growth of Staurastrum *sp.*

The characteristic of resistance to oxidation may ensure living cells of *Staurastrum* sp. entering into the CST, but cannot guarantee this alga becoming the dominant species in the tank. There should be some specific factors facilitating the reproduction of *Staurastrum* sp.

By comparing the differences of water parameters between PSP and CST (Table 3), high concentration of Fe in the CST is the most possible factor. N and P are the primary nutrients for algae. It is reported that P is the limited factor of Yuqiao reservoir [27]. However, there were thick sedimentations in both PSP and CST, which were the source of internal P and mitigated the P-limited condition. Thus, the moderate difference of P and NH_3-N concentration should not be the key factor facilitating the reproduction of *Staurastrum* sp. in the CST. As a comparison, there was a significant difference of Fe between the two tanks, and the concentration of Fe in the CST was almost four times greater than that in the PSP. Considering that Fe is an important microelement for algae, the different concentrations of Fe may result in the rapid growth of *Staurastrum* sp. in the tank.

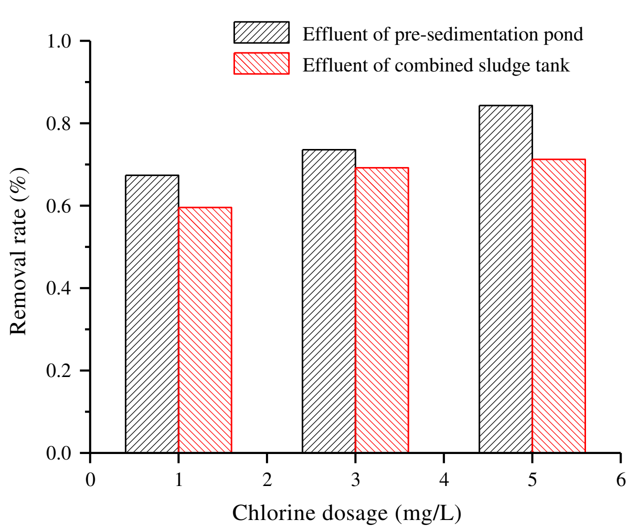

Fig. 7. Variation of Chl-a treated by chlorination and coagulation–sedimentation.

Culture experiment was performed to verify the effects of Fe on the reproduction of *Staurastrum* sp. and the results were shown in Fig. 8. Moderate concentration of Fe (0.6–2 mg/L) facilitated the growth of *Staurastrum* sp. and the highest growth rate was obtained at an initial Fe concentration of 0.6 mg/L. A low concentration of Fe (0.1 mg/L) inhibited the growth of *Staurastrum* sp.

The co-culture experiment of *Staurastrum* sp. and other algae was also performed. The diluted effluent of PSP (mixture of *Staurastrum* sp. and other algae) was incubated in the modified Knop medium with a Fe concentration of 1 mg/L for 3 d, and the variations of cell densities were shown in Table 4. The growth rate of *Staurastrum* sp. was much higher than that of the other algae, and the proportion of *Staurastrum* sp. also increased significantly. This result indicated that *Staurastrum* sp. was more competitive than the other ones under a high Fe concentration condition.

The algal culture experiment explained why the non-dominant species of algae in raw water became the dominant species in the CST. Fe is one of the most important nutrients for the growth of algae. It is reported the formation of high-nutrient, low-chlorophyll regions of the ocean can be attributed to the lack of iron in these regions [28]. Fe is also necessary for *Staurastrum* sp. This study indicated that *Staurastrum* sp. favors a moderate concentration of Fe and grow slowly under a low concentration. In raw water, the average concentration of Fe was 0.14 mg/L, which cannot meet the nutritional requirements of *Staurastrum* sp and resulted in the alga cannot be a dominant species in raw water. However, in the CST, the residual coagulant increased the concentration of Fe to 0.58 mg/L, which fell within the suitable range for the growth of *Staurastrum* sp. Under this condition, *Staurastrum* sp. grew much more rapidly than the other algae, and gradually became the dominant species.

It can be inferred that *Staurastrum* sp. became the unique dominant species in the CST via the following procedure. At the beginning, some survived cells of *Staurastrum* sp. entered into the CST with the recycled water streams, and grew in the tank. Then, the amplified *Staurastrum* sp. went back to the treatment process. Because of the inefficient inactivation by pre-oxidation, more survived cells re-entered and regrew in the CST. The density of *Staurastrum* sp.

Table 3
Comparisons of water quality between raw water and effluent of CST (data were collected from June to August, 2007)

Water source	Water temperature (℃)	pH	Turbidity (NTU)	Alkalinity ($CaCO_3$, mg/L)	COD_{Mn} (O_2, mg/L)	NH_3-N (mg/L)	P (mg/L)	Fe (mg/L)
Raw water	24.5–27.8	7.4–8.3	4.8–13.6	101.4–138.8	2.82–4.24	0.021–0.076	0.030–0.053	0.11–0.15
Effluent of CST*	25.0–28.5	7.8–8.2	5.2–6.8	90.5–105.4	4.29–5.15	0.046–0.103	0.024–0.036	0.53–0.67

*CST: combined sludge tank.

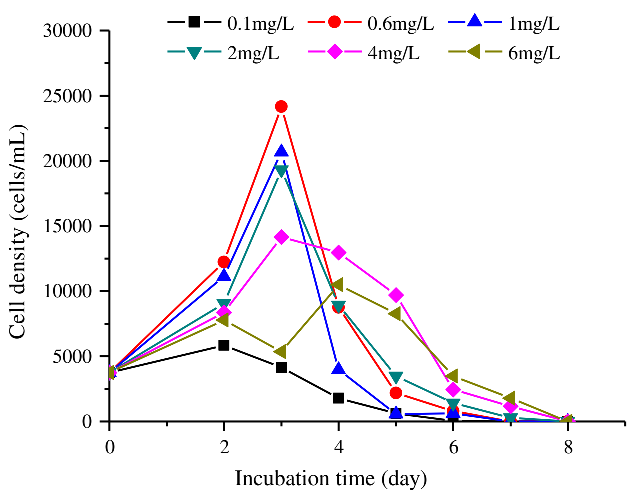

Fig. 8. Growth curve of *Staurastrum* sp. with different initial concentrations of Fe. Growth conditions: 25 ± 1℃, 12 h light/12 h dark, and 3,300 lx.

increased and accumulated with the continuous recycle of sludge water and backwash water. Finally, *Staurastrum* sp. became the dominant species in the CST, and disturbed the operation of WTP.

3.3. *Discussion about preventing the reproduction of* Staurastrum *sp. in the CST*

The reproduction of *Staurastrum* sp. in the CST depends on two conditions as discussed in section 3.2: (1) living cells can enter into the CST; and (2) CST provides favorable conditions for the growth of *Staurastrum* sp. Thus, cutting off the recycle pathway of *Staurastrum* sp. and destroying favorable growing conditions may be promising methods to solve the problem of algal reproduction caused by the recycle of sludge water and backwash water.

3.3.1. *Cutting off the recycle pathway*

Changing oxidants may be a feasible method to solve this problem, since chlorination was inefficient for the removal of *Staurastrum* sp. as shown in Figs. 6 and 7. A bench-scale oxidation experiment showed chlorine dioxide can inactivate *Staurastrum* sp. as efficiently as the other algae (Fig. 9). It can be inferred that chlorine dioxide can reduce the survived algal cell amount and thus limit the reproduction of *Staurastrum* sp. in the CST.

It is also feasible to remove the algae from the water streams by microfiltration or clarification prior to the recycle procedure. In fact, a clarification process has been adopted to remove the residual algal cells and suspended solids prior to the recycle of sludge water and backwash water since 2008, and *Staurastrum* sp. disappeared from then on. This phenomenon indicated cutting off the recycle pathway of *Staurastrum* sp. is effective. However, the construction and the operation costs should be considered. Because the hot summer only lasts less than 3 months in Tianjin, it may be uneconomic to install the treatment facility just for the removal of algal cells.

Table 4
Variations of cells densities of *Staurastrum* sp. and other algae in the modified Knop medium with a Fe concentration of 1 mg/L after three-day incubation

	The total		*Staurastrum* sp.		
	Density (cells/L)	Growth rate (%)	Density (cells/L)	Growth rate (%)	Proportion (%)
0 d	4,960	354.40	1,670	643.82	33.70
3 d	22,540		12,440		55.17

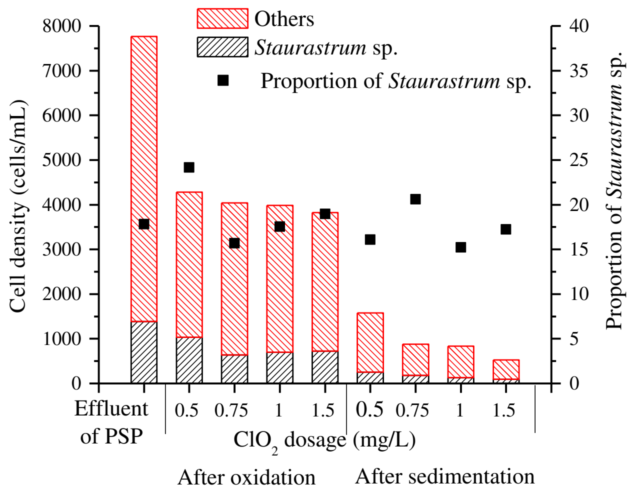

Fig. 9. Variation of algal densities in the effluent of PSP treated by ClO_2 and coagulation–sedimentation.

3.3.2. *Destroying the favorable growing conditions in the CST*

High concentration of Fe from the residual coagulant (ferric chloride) caused the reproduction of *Staurastrum* sp. Using aluminum-based coagulant instead of ferric chloride can minimize the concentration of Fe in the CST and prevent the growth of *Staurastrum* sp. However, this method cannot inhibit the growth of other algae. It is possible that some other species would replace *Staurastrum* sp. to be the new dominant algae in the CST.

A fundamental way is to minimize the favorable conditions for all the algae, such as treating the sludge to remove nutrients prior to the discharge into the CST, shading the tank, or increasing the flow velocity by setting guide walls. However, these methods will increase the construction cost.

In the September of 2007, an investigation was performed in another WTP (WTP-B) with the same raw water and the similar recycle procedure of sludge water and backwash water. The water production of the WTP-B was 1×10^6 m^3/d and the HRT of the CST was only 1 h. No *Staurastrum* sp. was detectable in the CST of WTP-B, and the result indicated that reducing the HRT in the CST can prevent the reproduction of *Staurastrum* sp. within WTPs, i.e. the reduction of favorable growth conditions for algae is an effective method for the control of *Staurastrum* sp.

The simplest way is blending the recycle water with raw water directly and canceling the CST. Because of the dilution effect by raw water, residual concentration of Fe cannot maintain the growth of *Staurastrum* sp., which would reduce the algal loading to the treatment process. The problem is that the contaminants and residual coagulants in the recycle water may accumulate in the PSP and cause some water quality problem in a long term. Thus, dredging is necessary if the CST is canceled.

4. Conclusions

In this study, a field survey was performed to investigate the variations of algal community structure and densities in a WTP employing a recycle procedure of sludge water and backwash water. Bench-scale experiments were performed to reveal the reasons that algae regrew within the WTP. The key findings of this research were listed below:

(1) Recycle of sludge water and backwash water resulted in *Staurastrum* sp., a non-dominant species in raw water, regrew in the CST, and became the unique dominant species.
(2) The reproduction of *Staurastrum* sp. increased the treatment loading to the WTP, clogged the filter, and deteriorated the quality of finished water.
(3) Chlorination was inefficient to inactive *Staurastrum* sp. cells, which lead to the entrance of living cells into the CST. High concentration of Fe from the residual coagulant facilitated the reproduction of *Staurastrum* sp. The two reasons resulted in the dominance of *Staurastrum* sp. in the WTP.
(4) Cutting off the recycle pathway and destroying the favorable growing conditions in the CST may be feasible methods to control the reproduction of *Staurastrum* sp. in the WTP.

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