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Performance of the unified clarifier packed with filter media (UC-FM) as a preliminary water treatment step

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ABSTRACT

The unified clarifier packed with filter media (UC-FM) is composed of three treatment tanks connected in series, and each tank is packed with porous filter media. As the downflow of untreated surface water is fed into the central cylinder of the tank, uniform upflow current in the outer area of the cylinder is concurrently made throughout the tank. The UC-FM system showed 80–90% removal in normal turbidity and above 90% removal in high turbidity. The average algae and COD removal by the system over 303 days operation were 80% and more than 90%, respectively. Precoagulation prior to the system improved the removal efficiency of the dissolved and particulate contaminants up to 99% without sand filtration or other consecutive treatment. The UC-FM system was operated any additional energy except for the intake of the raw water into the first tank. A negligible head loss was observed after almost 100 days operation and backwashing was not required.

Keywords: Water treatment; Filtration; Porous filter media; Coagulation

1. Introduction

Most water treatment plants (WTPs) in South Korea have been confronted with the troubles of high turbidity and algal biomass of the raw water [1,2]. The troubles mainly result from the fact that the water resources of many WTPs are located in the lower parts of rivers. High frequencies of algal blooms or high turbidity are considered as the primary problems in the water treatment process [3,4].

When algal biomass are expressed as chlorophyll-*a* (Chl-*a*) concentrations, Korean freshwaters are evaluated as eutrophic or hypereutrophic state with high fertilization [5]. There can be significant seasonal variation of algal blooms and turbidity in lower part of the Nakdong river—which is located in southeastern part of South Korea. The concentrations of planktonic algae in the source water of the Nakdong river were found to be over 100 μg Chl-*a*/L in the dry season such as February–April. The excessive occurrence of algae in raw water provokes a variety of problems in the water treatment process, especially in sedimentation and filtration. The rich content of algal derivative matter can cause taste and odor, or poor coagulation and flocculation. In addition, excessive suspended solids in raw water can cause additional problems in the process of water treatment [2]. Highly

Presented at the Fifth Annual International Conference on "Challenges in Environmental Science & Engineering—CESE 2012" Melbourne, Australia, 9–13 September 2012 turbid states persisted for long times after the flooding or raining during rainy season from June to September due to heavy soil erosion. Their frequencies have gradually increased in recent times. Examples of this problem are especially observed in the basins of the Nakdong river and Han River in Korea, where turbidity usually exceeded 1,000 NTU after intense rainfalls and extremely high turbidity persisted for long periods of time in the upstream reaches or lakes [6]. This impacted the downstream of the river for a distance of 300 km. The resulting high-turbidity water has a narrow range of coagulation conditions and poor flocculated solids strongly resist settling down in the water treatment process, as they have a greater particle surface area band, on the other hand, lower alkalinity and ionic concentration [7].

Algal blooms in the dry season and high turbidity in the rainy season have become the primary problems in WTPs [8,9]. No conventional treatment process would achieve the complete removal of the algae and their by-products so as to keep the effect to a minimum. Pretreatment using oxidants such as ozone, chlorine, and potassium permanganate has been shown to improve algae removal as result of algal inactivation [10]. A number of filtration and sedimentation techniques can be employed to reduce high turbidities in the source water down to levels considered acceptable for sedimentation or sand filtration. Another technique can be employed to reduce the numbers of natural particles and dissolved substances in the source water prior to the water treatment process. These pretreatment steps include prechlorination, pre-ozonation, biological filtration (using sand or granular activated carbon, or dissolved air flotation) [4,11].

The technology development for the algae and turbidity removal has focused on mostly chlorination, flocculation/sedimentation and floatation. However, direct filtration has recently been developed as a pressure from cost and energy constraints for the rapid development of economical and energy-efficient treatment technology [12,13]. The primary potential advantage of direct filtration is a reduction in the capital cost of the treatment facility as a result of elimination of the settling basins and elimination or significant reduction of the flocculation tank. Other benefits include a reduction in chemical dosages, resulting in decreased sludge production and less maintenance. Ngo et al. have developed a combined system of dual-media (floating media & sand) filter with the concept of using floating media as a flocculator and prefilter and sand as a subsequently polishing filter [14,15].

An unified clarifier packed with filter media (UC-FM) filtration system was installed at the field to be operated for 303 days as a pretreatment process for the removal of algae and turbidity. The purpose of the operation was to prove the capacity and optimization of the system in terms of algae and turbidity removal.

2. Materials and methods

2.1. UC-FM system

The UC-FM system is composed of three treatment tanks connected in series as shown in Fig. 1. As downflow of untreated raw water was fed into the central cylinder of the tank, uniform upflow current from the bottom in outer area of the cylinder was concurrently achieved throughout the tank. Three tanks were connected sequentially through the tank head. As a result, the system did not require any additional power except for the pumping the raw water up into the first tank. Approximately, 60% of each tank is packed with porous filter media called GreenBall (GB). The GB is made of polypropylene suitable to keep the substantial microbial growth upon its surface. Grain size, specific area, porosity, and density of the GB were 20 mm, 353 m^2/m^3, 31%, and 684.8 kg/m^3, respectively. The GB is classified as floating media because of the lower density and high porosity.

The experimental research was conducted with 2 UC-FM systems. The first system was a laboratory-scale having a diameter of 0.6 m and a height of 1 m as shown in Fig. 1(a). Effective bed depth and bed volume of the system were 0.7 m and 0.19 m^3, respectively. It was operated to evaluate the efficiency of the system with artificial suspensions as well as natural water. As shown in Fig. 1(b), the second system was a pilotscale of which a diameter and a height were 2.0 and 6.0 m, respectively. And effective bed depth and bed volume of the system were 4.0 m and 12.5 m^3, respectively. The system was operated for 303 days with influent of natural river water. Due to different dimensions, the first and second systems were packed with different sizes of GBs. The operational flow rates of the systems were also different which were 1.4–33.4 m^3/d for the first and 100–400 m^3/d for the second.

2.2. Raw water

The experiments were carried out with two different kinds of raw water, artificial suspensions and natural river water. The artificial suspensions were prepared with Nakdong River water spiked with

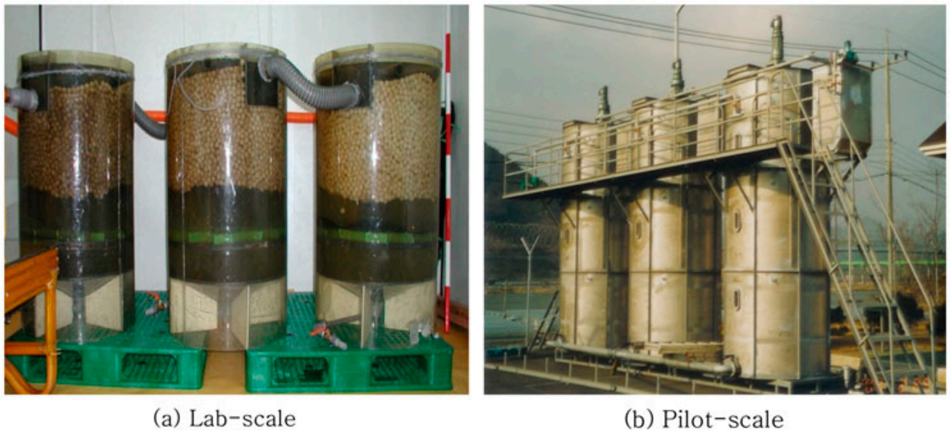

Fig. 1. Photos of UC-FM system.

three different kinds of suspended particles until a specific concentration of suspensions was achieved. Three suspended particles were loess, kaolin, and bentonite. The concentrations of suspensions were measured as turbidity. The concentration was controlled from 100 to 900 NTU in each experiment.

The natural river water was pumped from Nakdong River and used directly. The quality of raw water in terms of COD, Chl-*a*, and turbidity was obtained from a monitoring station managed by the Water Authority of Busan Meropolitan City. The median values of COD, Chl-*a*, and turbidity over 303 days operation were 5.3 mg/L (2.9–9.0 mg/L), 50.3 μg/L (4.0–143.5 μg/L), and 10.3 NTU (4–564 NTU), respectively. In the period of algal bloom, value of turbidity disagreed with high Chl-*a* concentration or algal biomass showed changelessness or monotony. High turbidity water was observed primarily during the periods of intensive rain from July to September.

2.3. Analytical methods

The performance of the system was evaluated based on the removals of turbidity and Chl-*a* as well as other parameter such as COD, TN, and TP. Turbidity of the system was monitored by HACH 2100N Turbidimeter. Other parameters were analyzed according to Standard Methods for the Examination of Water and Wastewater.

3. Results and discussion

3.1. Lab-scale system's operation

3.1.1. Effect of suspended particles

The turbidity of law water was adjusted for 1 h operation at 100 NTU, and the flow rate was 5.0 L/min. Removal characteristics of the suspended particles were shown in Fig. 2 in terms of turbidity removal. Fig. 2 shows the turbidity removal by 1st, 2nd, and 3rd reactor step by step.

As shown in Fig. 2, a similar tendency of removal was observed in loess and kaolin. They were mostly removed by the 1st reactor. On the other hand, bentonite was mostly removed by the 3rd reactor. Total removals of loess, kaolin, and bentonite were 84, 90, and 64%, respectively. Particle sizes and zeta potentials for the suspended particles were analyzed and shown in Table 1. Zeta potentials of all the particles were similar, but average particle sizes were significantly different in particular in bentonite which might cause the different removal tendency. The removal mechanism of the UC-FM is sedimentation by gravity as well as filtration by GB media. Particles are removed by sedimentation during downflowing into central cylinder and then upflowing in outer tank. Then, they are experienced the filtration by GB media during upflowing. Ben Aim et al. have reported from their extensive experimental data that the removal of the particle over 1 μm increases with an increase in

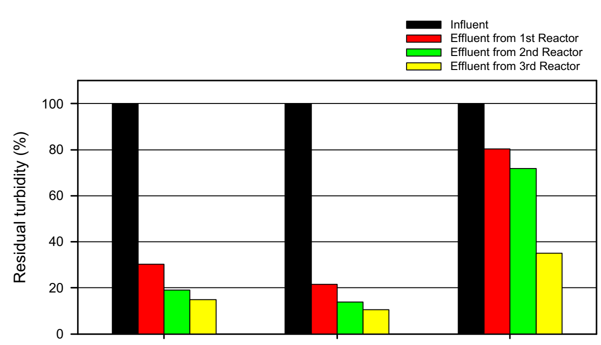

Fig. 2. Removal of three suspended particles by UC-FM.

Table 1
Particle size and zeta potential of three suspended particles

	Average particle size (μm)	Zeta potential (mV)
Loess	13.9	−12.0
Kaolin	9.3	−15.8
Bentonite	4.9	−13.5

particle size [16]. Through experimental and theoretical approach, Leitschkis et al. showed that the particles near −10 mV of zeta potential can be removed by the mechanical rather than by the adsorptional [17]. That might be the reason that the relatively bigger particles—loess and kaolin were mostly removed by the 1st reactor through which bentonite easily passed because of the smaller size. However, even the bentonite could not be successful in passing through the whole three consecutive reactors.

3.1.2. Effect of influent turbidity and flow rate

Raw water in this experiment was prepared by adding loess into Nackdong River water. Figs. 3 and 4 show the experimental results with different flow rate and influent turbidity, respectively.

As shown in Fig. 3, the removal was slightly decreased 82–62% as the flow rate increased. The removal of 62% at the flow rate of 23 L/min was also amazing value, because it was achieved only by the filtration without coagulation. This result was similar to what were reported by several other researchers who found that at low filtration velocity, FM filtration provided excellent total suspended solids (TSS) removal but was considerably reduced at higher filtration velocity [12,14,18]. Steicke et al. have reported from the experimental results with downflow with

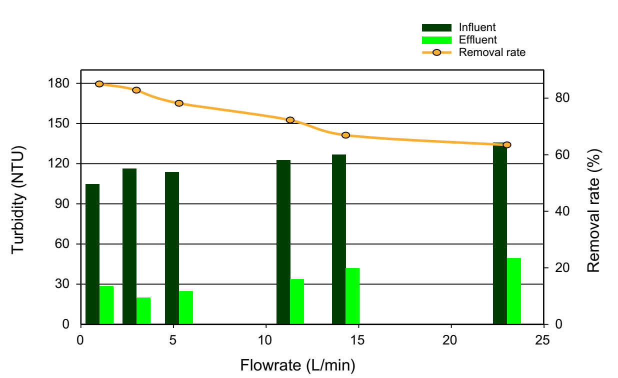

Fig. 3. Effect of flowrate on particle's removal.

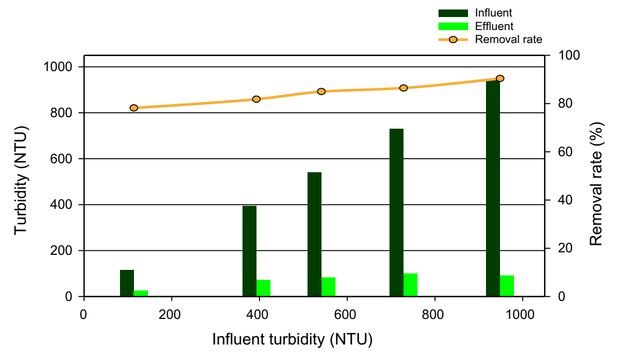

Fig. 4. Effect of influent turbidity on particle's removal.

floating-media and downflow with sand that TSS removal reduced 80–31% as velocity increased 8.8–32 m/h [18]. The flow rate of 23 L/min was 117 m/day converted into filtration velocity which is in the range of fast sand filtration.

Fig. 4 shows slight increase in the removal as influent turbidity increases. The value of 80% removal at 100 NTU increased up to 90% at 900 NTU. The result implies that UC-FM has a sufficient capability in water treatment for an emergency such as heavy rainfall during which high turbid water sometimes more than hundreds of NTU comes into WTPs. A laboratoryscale UC-FM system operation was performed for 7 days using Nakdong River water as influent. The flow rate was also fixed at 5.0 L/min in the operation. The influent was varied continuously between 20 and 40 NTU but the effluent showed a constant value of 5 NTU. Constant removal of more than 80% was achieved from the operation.

3.2. Pilot-scale system's operation

Pilot-scale UC-FM system was operated for 303 days using Nakdong River as raw water. The effluents from 1st, 2nd, and 3rd reactors were sampled for the analysis of turbidity, Chl-*a*, COD, TP and TN. The operation was stopped during heavy rainfall season, because the variations of flow rate and turbidity were too significant. Observations on the cases of heavy rainfall and algal bloom were separately performed after 303 days of operation. The removals of each item by 1st, 2nd, and 3rd reactors are shown in Fig. 5(a)–(e). A comprehensive result is shown in Fig. 6.

As shown in Fig. 5(a), the turbidity of raw water was in the range of 4.5–28 NTU. The values did not included for the operation of heavy rainfall season during which the turbidity normally increases more than hundreds of NTU. The turbidity of final effluent

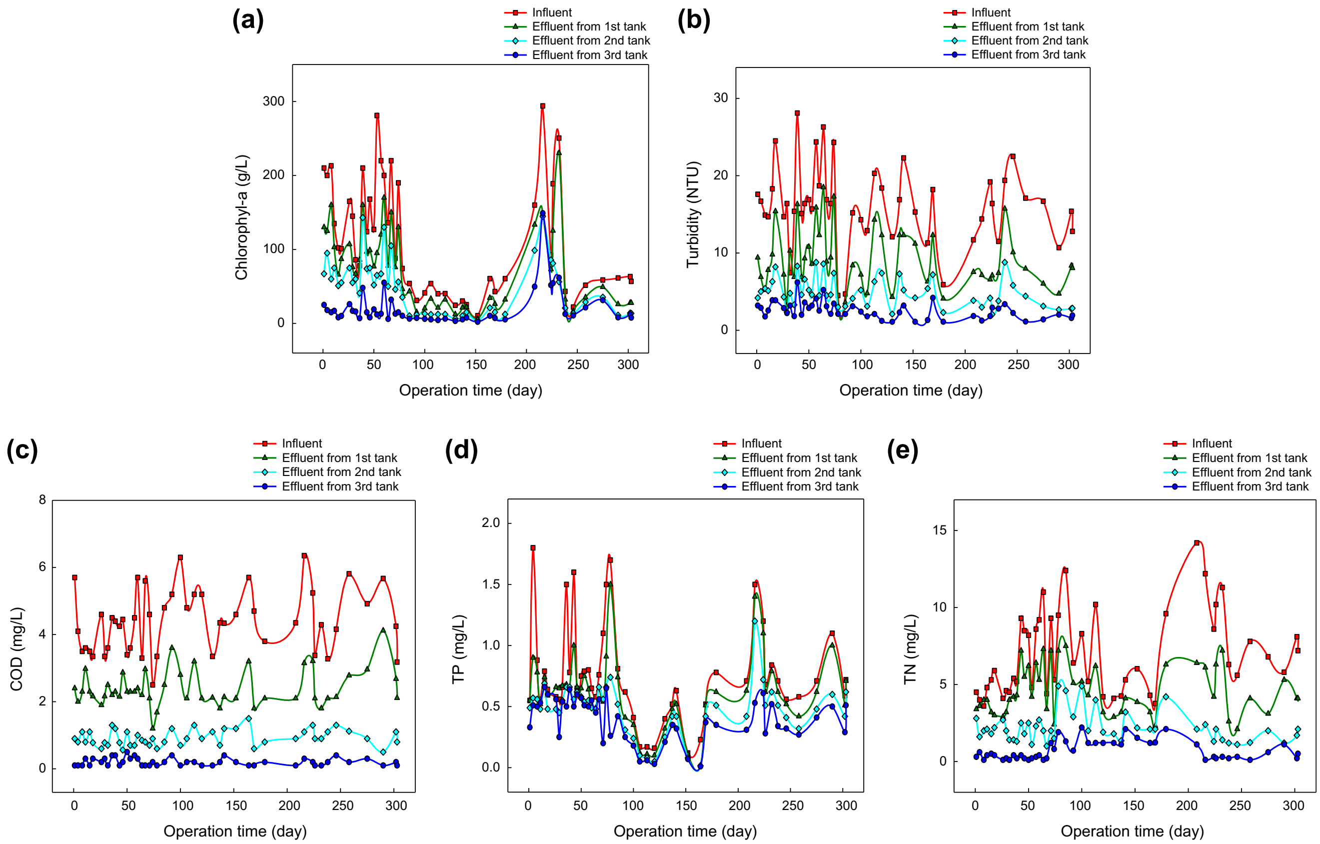

Fig. 5. (a) Chl-*a*, (b) turbidity, (c) COD, (d) TP, and (e) TN removal over 303 days operation.

was 1.1–14.2 NTU. Average removals by 1st, 2nd, and 3rd reactors were 43, 25, and 12%, respectively. Total removal of turbidity by the system was averagely 81% for 303 days.

Chl-*a* concentration of Nakdong River was high when its turbidity was low, but it was low at high turbidity such as heavy rainfall season. The reciprocal relationship was found in Nakdong River between Chl-*a* and turbidity. The Chl-*a* concentration during the operation was 249 μg/L of maximum, 10. 5 μg/L of minimum and 113.4 μg/L of average. Microalgae was found a significantly high rate in the concentration. As shown in Fig. 5(b), average removals by 1st, 2nd, and 3rd reactors were 33, 24, and 24%, respectively. Total removal was averagely 82% which was similar with turbidity removal.

The observation of UC-FM's removal of dissolved materials such as COD, TP, and TN showed that influent COD was averagely 4.4 mg/L with small deviation and, TP and TN were in the ranges of 3–14 mg/L and 0.12–1.8 mg/L, respectively. Average COD of final effluent was 0.2 mg/L which means a 95% of total removal as shown in Fig. 5(c). However, the removal of TP by the system was relatively low. Total removal was observed averagely 46% but it increased up to 50–55% except the unstable state of initial operation (Fig. 5(d)). On the other hand, the removal of TN was relatively satisfactory. The average TN of influent was 6.98 mg/L and was reduced 89% by the system (Fig. 5(e)).

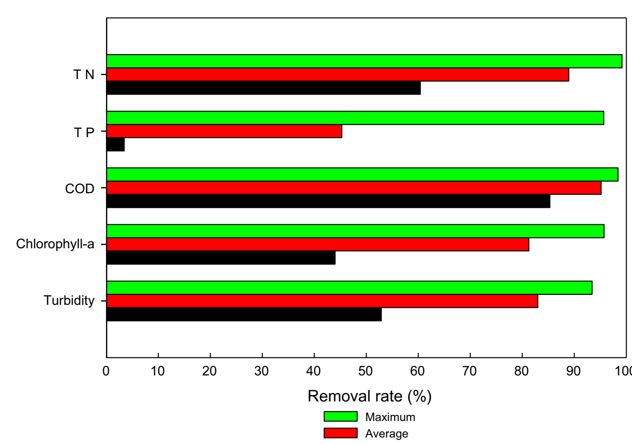

Fig. 6. Summary of 300 days operation.

Fig. 6 shows minimum, maximum and average removals of turbidity, Chl-*a*, COD, TP, and TN by UC-FM system obtained from 303 days operation. UC-FM system showed more than 80% in the removals of turbidity, Chl-*a*, and COD. The removal of COD was even more than 90%. The result is amazing because it was attained only from the filtration without any addition of chemical for flocculation. The significantly high removal of even the dissolved materials such as COD and TN might result from biofiltration of the UC-FM system. A thick biofilm could be observed on the surface of GB media and the operation was able to be operated without sludge discharge for more than 6 months [19].

July and August are rainy season in Korea during which some of WTPs stop the intake of water because of high turbidity up to several hundreds of NTU in water resources. Algal bloom in water resources also causes significant problem in WTPs. The capability of UC-FM system to treat the problem was tested with continuous monitoring the operation during July–August for high turbidity and April–July for algal bloom. Fig. 7 shows the operational result on high turbid influent caused by heavy rainfall. The turbidity of influent was significantly varied up to more than 350 NTU but that of effluent showed a constant value less than 20 NTU. Average removal was 67% which was slightly less than the removal of non-rainy season's operation—it was more than 80% mentioned above. Fig. 8 shows the operational result from April to July for algal bloom treatment. Chl-*a* concentration of influent was 22–299 μg/L and that of effluent was 8–149 μg/L. Minimum, maximum, and average removals were 44, 87, and 67%, respectively.

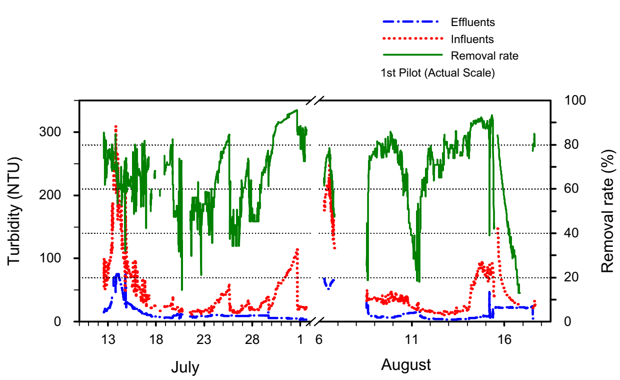

Fig. 7. Influent and effluent turbidity and removal efficiency (high turbidity influent).

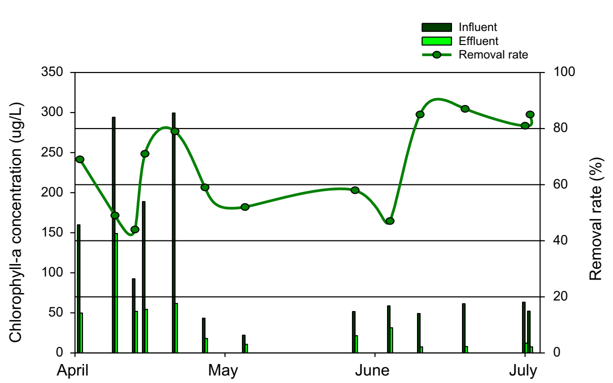

Fig. 8. Chl-*a* removal efficiency.

4. Conclusions

In this study, the following conclusions could be drawn according to the experimental results.

(1) From the operation of laboratory scale UC-FM system, it was found that large particle (more than 10 μm) such as loess and kaolin could be removed by the 1st reactor of the system while even smaller particle (less than 5 μm) like bentonite could be successfully removed by the three consecutive reactors of the system. Total removals of loess, kaolin and bentonite were 84, 90, and 64%, respectively. The operation also showed that as the flow rate increased 1–23 L/min the removal of particles decreased 82–62%, and as influent turbidity increased 100–900 NTU the removal increased 80–90%. The consistent operation of the system for 7 days showed a constant removal of turbidity more than 80%.

(2) From the operation of pilot-scale UC-FM system for 303 days, average removals of turbidity, Chl-*a*, COD, TN, and TP were 81, 82, 95, 89, and 46%, respectively. The operation of the system during high turbid season such as heavy rainfall (July and August) showed 67% of average removal of turbidity. The system could also remove 67% of Chl-*a*, when it is operated during the season of microalgae bloom (April–July).

Acknowledgment

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