Evaluation of upgrading a full-scale activated sludge process integrated with floating biofilm carriers

Shijian Ge, Yunpeng Zhu, Shuang Qiu, Xiong Yang, Bin Ma, Donghui Huang and Yongzhen Peng

ABSTRACT

This study evaluated the performance of a full-scale upgrade of an existing wastewater treatment plant (WWTP) with the intermittent cyclic extended aeration system (ICEAS), located in Qingdao, China. The ICEAS system was not able to meet effluent standards; therefore, a series of modifications and control strategies were applied as follows: (1) floating plastic carriers were added to the tank to aid biofilm formation; (2) operation parameters such as mixing and aeration time, feeding rate, and settling time were adjusted and controlled with a real-time control system; (3) a sludge return system and submersible water impellers were added; (4) the aeration system was also improved to circulate carriers and prevent clogging. The modified ICEAS system exhibited efficient organic and nutrient removal, with high removal efficiencies of chemical oxygen demand (89.57 ± 4.10%), NH_4^+-N (95.46 ± 3.80%), and total phosphorus (91.90 ± 4.36%). Moreover, an annual power reduction of 1.04×10^7 kW·h was realized as a result of these modifications.

Key words | biofilm, biological nutrient removal, ICEAS, wastewater, WWTP

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INTRODUCTION

During the last century, population growth, industrialization, and urbanization have all contributed to greater environmental pollution, especially eutrophication of aquatic environments. Eutrophication results in oxygen-depleted 'dead-zones', toxic compound production, reduced photosynthetic activity and transparency, and decreased biodiversity (Kortstee *et al.* 1994). Nitrogen and phosphorus contribute most to eutrophication. These nutrient emissions are generated in large quantities by municipal wastewater treatment operations, agricultural fertilizer leaching, and animal manure release in rural areas. Strict standards have been imposed on wastewater treatment plants (WWTPs) to reduce the nitrogen and phosphorus into water bodies. Therefore, it is imperative to find a way to upgrade existing WWTPs while maintaining low emission standards.

In general, WWTPs seeking to reduce their emission levels have either invested in new tanks or retrofitted existing infrastructure with advanced technologies. Due to lower costs, most WWTP upgrade projects have adopted the latter approach (Kaindl 2010). However, meeting the high nitrogen removal standards proved to be challenging, especially for activated sludge systems, due to the limited substrates available for denitrification and low temperature in winter seasons. Some WWTPs have successfully combined two processes (attached and suspended biomass) by adding biofilm carriers into the activated sludge system (Ge *et al.* 2012b; Zhang *et al.* 2014), so that high biomass concentrations can be obtained without overloading in the secondary clarifiers, and the long sludge retention time (SRT) due to biofilms can be achieved for nitrifying bacteria (Randall & Sen 1996), and sufficient nitrification can even be processed in winter seasons (Sriwiriyarat & Randall 2005; Mannina & Viviani 2009). Therefore, combining the existing activated sludge process with the biofilm process is a

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competitive and economical alternative for the upgrading of overloaded plants.

In this study, the upgrading of a full-scale WWTP, originally operated in the intermittent cyclic extended aeration system (ICEAS), by the addition of floating carriers was investigated. All upgrades in infrastructure were optimized with the existing configurations, and the cost was also evaluated. This full-scale study will enable a rational design and operation of enhanced biological nutrient removal systems, and lead to increased process stability and efficiency of WWTPs.

MATERIALS AND METHODS

Field site description

The upgrade project focused on the first phase of a full-scale WWTP in Qingdao, China, which treated domestic wastewater with a design flow of 1.0×10^5 m^3/d. The plant consisted of two activated sludge systems for organics and nutrient removal. ICEAS was used in the first phase (Figure S1(A); available online at http://www.iwaponline.com/wst/070/370.pdf), and the anaerobic/anoxic/oxic process for the second phase (Ge *et al.* 2012b). Both systems shared the same mechanical treatment facilities, such as thick grid station, influent pump station, thin grid station, aerated grit chamber, and primary clarifier.

In the ICEAS system, there were eight stainless steel cylindrical reactors, divided into two parallel systems, each with a series of four tanks. Each reactor (diameter 38 m × height 6.2 m) comprised an anoxic selector and a reaction zone, and had a working volume of 5,894 m^3. Figure S1(B) (available online at http://www.iwaponline.com/wst/070/370.pdf) illustrates the operation sequence used before upgrade. It had a fixed cycle duration of 6 h with a continuous filling phase, together with a 1 h mixing phase, 3 h aeration phase, 0.8 h settling phase, and 1.2 h decanting phase. The filling ratio was in the range of 0.3–0.35. The average mixed liquor suspended sludge (MLSS) concentration was controlled at approximately 4,000 mg/L, with a SRT of about 15 d.

Wastewater and packing carrier medium

The raw wastewater was collected from the local municipal pipe network and several industrial plants. The characteristics of the wastewater were as follows (mg/L): alkalinity 370–490; chemical oxygen demand (COD) 174–555; biochemical oxygen demand (BOD_5) 44–240; total Kjeldahl nitrogen 29.4–52.2; NO_3^--N 0–6.44; NO_2^--N 0.046–0.46; total phosphorus (TP) 3.02–12.4; PO_4^{3-}-P 2.04–11.9; pH 6.75–8.07.

A patented polymer material carrier (CN200720036902.6) was used as the packing medium to immobilize the microorganism. The carrier had a specific surface area greater than 500 m^2/m^3, and porosity greater than 95% with a density of 0.95 g/cm^3. In addition, all water samples were analyzed after filtration with 0.45 μm filter paper. COD, NH_4^+-N, NO_2^--N, NO_3^--N, PO_4^{3-}-P, TP, MLSS, and sludge volume index (SVI) were analyzed according to *Standard Methods* (APHA 1998).

RESULTS AND DISCUSSION

Overview of the original ICEAS performance

The original design parameters and treatment capacities were selected based on the requirements of the Chinese first-B discharge standards (TN 20 mg/L, NH_4^+-N 8 mg/L, TP 1.0 mg/L, and COD 60 mg/L). However, the real inflows (5.7×10^4 m^3/d in Figure 1(d)) far exceeded the maximum design flows (5.0×10^4 m^3/d), thereby resulting in unsatisfactory nitrogen and phosphorus concentrations in the effluent. Figure 1(a)–1(c) shows the original ICEAS performance in 2 years, including COD, NH_4^+-N, and TP removal efficiencies and power consumption. High organic removal was achieved (i.e., removal efficiency = 89.2 ± 3.2%), but it is worth noting that about half of influent COD was eliminated during aerobic oxidation. Furthermore, although relatively low influent NH_4^+-N concentrations were achieved, ranging from 13.0 to 38.4 mg/L, the removals fluctuated with the effluent concentration and removal efficiency (i.e., 8.31 ± 5.53 mg/L and 67.8 ± 19.5%, respectively). More than 20 mg/L of TN on average in the effluent was observed. The TP removals were more stable, but still had a low removal efficiency of 68.3 ± 4.9% and high effluent concentration of 2.21 ± 0.42 mg/L, respectively. Therefore, the primary problems existing in the ICEAS system were incomplete nitrification and denitrification, insufficient phosphorus release and poor phosphorus removal, as well as undesired utilization of influent substrates. We attributed the problem to improper operation parameters applied and undesired process designs, which failed to provide desired growth environments for functional microorganisms. In addition, the energy consumption over time, before the upgrade, is illustrated in Figure 1(d).

Proposed modifications

In view of the existing problems associated with the original ICEAS system, the following modifications were implemented, as illustrated in Figure 2.

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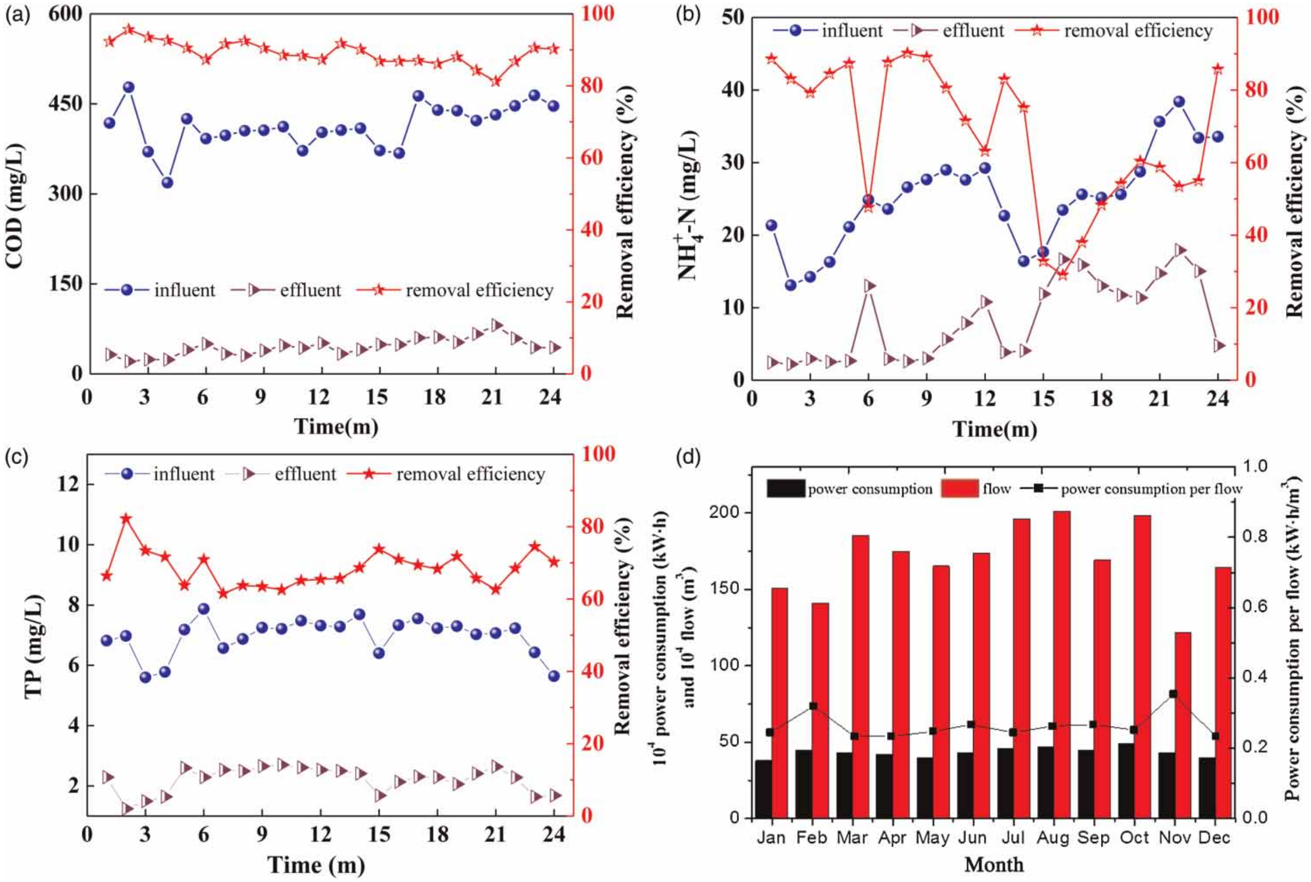

Figure 1 | Profiles of (a) COD, (b) NH_4^+-N, (c) TP removals, and (d) inflows and power consumption in the original ICEAS system.

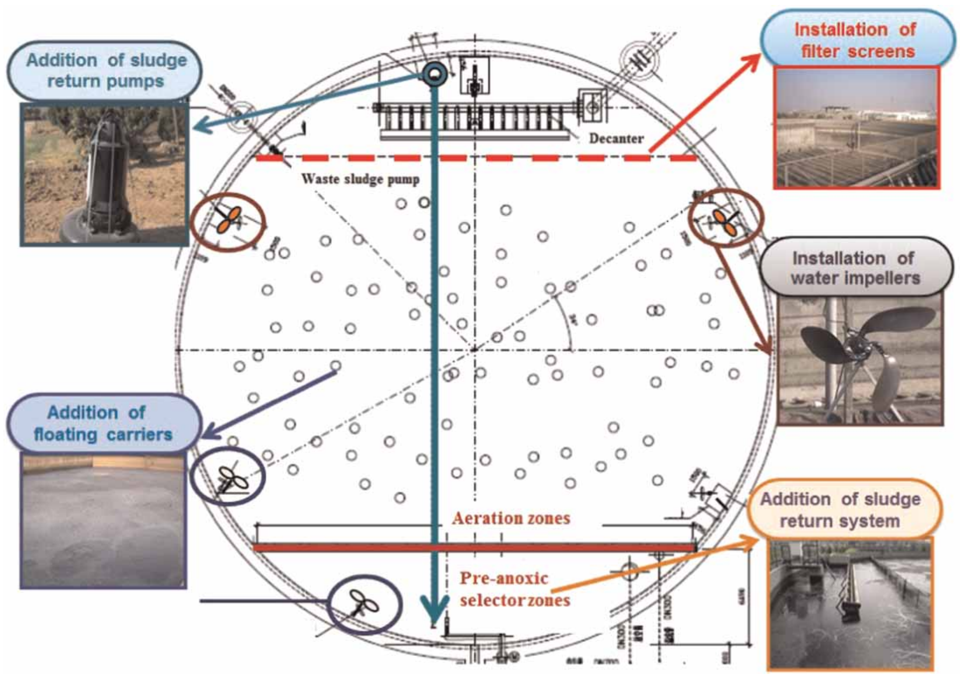

Figure 2 | Layout of biological treatment units in the updated ICEAS process.

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- A sludge return system and new pumps from aeration zones were added to the pre-anoxic selectors in order to ensure sufficient MLSS in selectors.
- Floating plastic carriers were added into aeration zones to enhance nitrification, and filter screens were installed in the final sections of aeration zones in case of carrier outflow and clogging.
- New submersible water impellers were installed in aeration zones to provide adequate sludge mixing and carriers' circulation.
- Filling in the aeration phase was terminated to avoid the influent carbon sources being oxidized.
- The anoxic mixing time was prolonged while the aeration was shortened, in order to improve the anoxic denitrification and the utilization of influent substrates.
- Most importantly, the operational sequence was optimized with a real-time control system as shown in Figure 3. The filling phase started simultaneously with the settling and sludge discharge phase. The control programme initiated the decanting phase at a pre-set time, meanwhile the sludge return pumps started to work. When both the filling and effluent discharge stopped at the designated time points, the submersible impellers were activated. Then the aeration system would be programmed to launch after the sludge return and mixing ended. During the aeration phase, the impellers kept on working to facilitate adequate contact between the pollutants and sludge. Then the next cycle followed after the aeration phase achieved the set time.

WWTP performance after upgrade and permit limits

System start-up and biofilm formation

To start the system, the biological tank with the activated sludge and wastewater was filled to a final MLSS

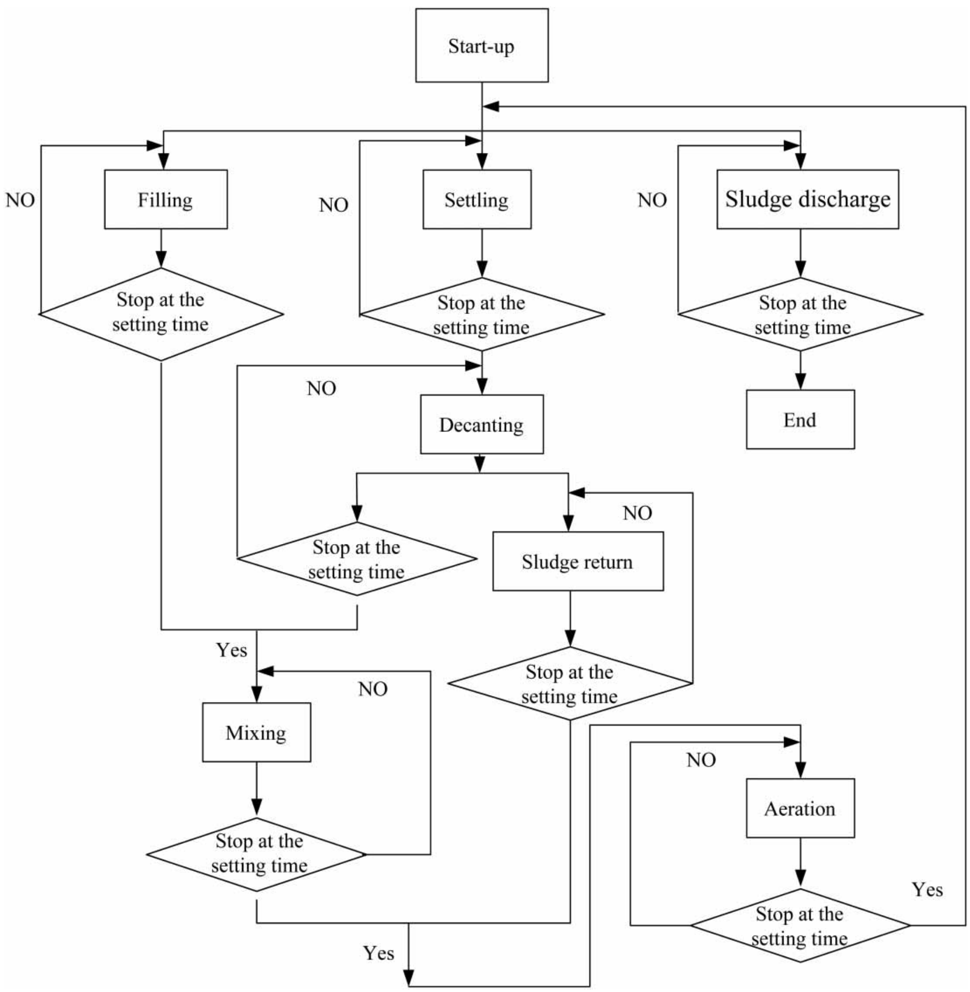

Figure 3 | Control strategy for the updated ICEAS process.

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concentration of about 1,000 mg/L. Then, the system was operated in batch for approximately 12 h under aeration with adequate oxygen supply. Such operation lasted 3 days. Afterwards suspended carriers were added, and meanwhile additional activated sludge was dosed to enrich the microorganism populations. According to the batch test described in the supplementary information and Figure S2 (available online at http://www.iwaponline.com/wst/070/370.pdf), the nitrification rates increased with the increase of the tested filling ratios (0, 15, 30, and 45%). Due to economic considerations, 15% was chosen as the real dose in the ICEAS upgrade project. Again, the system was initially operated in batch with a 6 h periodic cycle in phase 1 as shown in Figure 4 (a). Both COD and NH_4^+-N removals gradually recovered, mainly through the suspended activated sludge instead of biofilms on carriers. Limited biofilms on Day 5, but continuous biofilm growth on Day 10, were observed (Figure 4(b)). In Phase 2, a continuous-flow, completely mixed mode was applied to facilitate biofilm formation and to washout part of the suspended sludge. The COD and NH_4^+-N removal efficiencies decreased, but the enriched biofilms, together with protozoa, rotifers, and nematodes, were attached on the carriers' surface on Day 15 (Figure 4(b)). It implied successful biofilm formation occurred on the carriers. Afterwards, the intermittent inflow and aeration were applied to the system in Phase 3. As expected, the high quality of effluent with low COD and NH_4^+-N concentration was obtained, due to the biofilm and suspended sludge. To maximize the biofilm, uniform feeding and an air distribution system were provided in the design (details in the section 'Further remarks and economic analysis'), and the appropriate pollutant loading rate was applied.

Steady-state performance after modification

During the upgrade, which occurred in three phases, the original plant layout of tank #1 was operated as a control group in parallel with tank #2, which was upgraded.

In Phase 1, continuous feeding in the aeration phase was terminated. Then the 3-hour intermittent feeding cycle began,

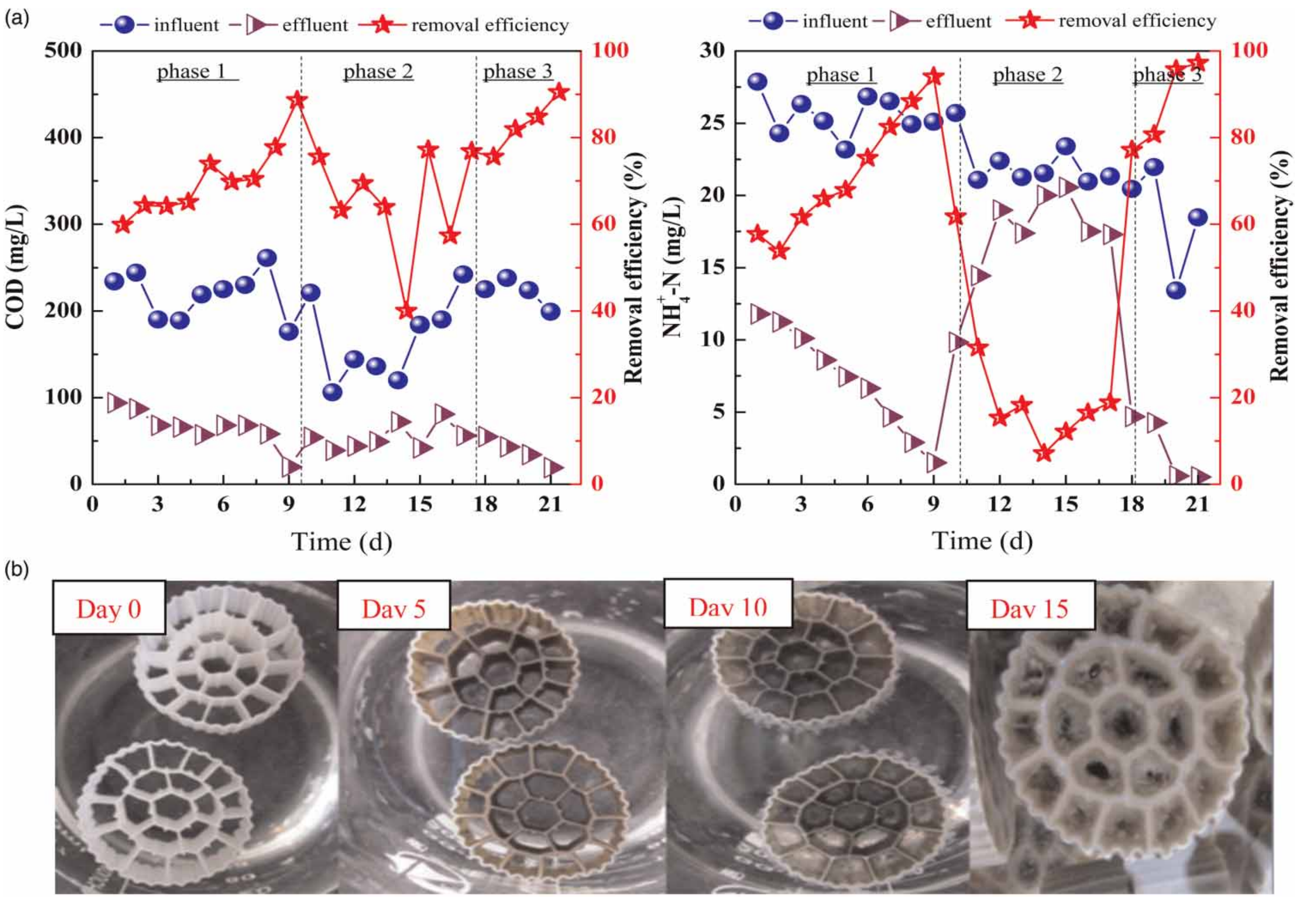

Figure 4 | (a) COD and NH_4^+-N removal during the biofilm formation in ICEASE; (b) biofilm formation on the surfaces of carriers.

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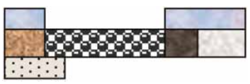
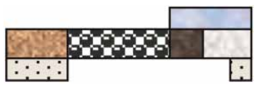
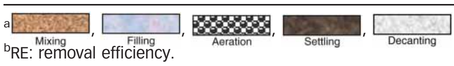
which was accompanied by a mixing, settling, and decanting process. The newly implemented sludge return system started with the mixing process and lasted 1.5 h to ensure an appropriate MLSS concentration for the pre-anoxic selector. The other operational parameters were the same as the previous process. Table 1 summarizes and compares the effluent qualities in both tanks for different scenarios. Results show that the amendment of operational modes in tank #2 remarkably improved the system performance and the pollutant removal efficiencies, especially for NH_4^+-N and TN. For example, the NH_4^+-N removal efficiency was 64.80 ± 25.49% in tank #1, whereas it was 92.38 ± 6.54% in tank #2; by contrast, the effluent TN concentration was decreased from 18.2 ± 3.1 mg/L to 14.2 ± 2.8 mg/L on average, and thereby the TN removal efficiency was enhanced by approximately 17.6%. Similar patterns were observed for TP and COD. The improvement can be attributed to adequate aeration (dissolved oxygen >3.0 mg/L) and enriched biofilms for nitrification (Masic *et al.* 2010; Bassin *et al.* 2011) Also, the new concentrated feeding regime and sludge return in the mixing and decanting processes enabled denitrification and anoxic phosphorus release (Elefsiniotis & Li 2006; Xu *et al.* 2011; Ge *et al.* 2012a). It should be noted, however, the TN and TP removal efficiencies were still low (35.21 ± 15.97 and 68.35 ± 15.48%, respectively) mainly due to low carbon levels in the influent (150.23 ± 103.71 mg COD/L on average).

Phase 2 was conducted in winter with the temperature at 8.0–12.4 °C. The decreased temperature and the simultaneous end of mixing and feeding resulted in diminished denitrification. Thus the mixing time was elongated by 0.5 h at the expense of the aeration length, and meanwhile the submersible water impellers were kept working in the settling and decanting process to ensure thorough mixing. Results indicated that, despite shorter aeration time in tank #2, greater nitrification was observed than that in tank #1 (removal efficiency of 92.19 ± 4.53 vs. 81.94 ± 10.27%). Indeed, denitrification and TN removal were also improved, even though TN removal efficiency was still suboptimal due to low temperature conditions and insufficient substrates. Similar observations were obtained for TP and COD removals (Table 1). It should be noted that the higher pollutant removals observed in Phase 2 compared to Phase 1 could be explained by the greater rainfall occurring in Phase 1 and different pollutants in the influent such as industrial chemical inflows. In Phase 3, the sludge settling characteristics were further improved by the 17 min elongated settling time, as indicated with a SVI generally less than 120 mL/g. Finally, the process was operating with great stability (Table 1) and with excellent sludge settleability (results not shown). This was likely due to the pre-anoxic selector provided in the upgraded bioreactor layout and sufficient settling time. The pre-anoxic selector could improve the anaerobic environments with less oxygen in the system. This not only aided the phosphorus release but also inhibited the growth of filamentous bacteria that could cause bulking sludge.

Table 1 | Comparison of pollutant removal performance in original and upgraded processes

		Phase 1		Phase 2		Phase 3	
Operational mode[a]							
Item		Effluent (mg/L)	RE[b] (%)	Effluent (mg/L)	RE (%)	Effluent (mg/L)	RE (%)
NH_4^+-N	#1[c]	6.50 ± 4.3 (40)[d]	64.80 ± 25.49	5.94 ± 3.43 (32)	81.94 ± 10.27	5.41 ± 2.70 (34)	83.62 ± 5.87
	#2[c]	1.57 ± 1.6 (40)	92.38 ± 6.54	2.55 ± 1.44 (32)	92.19 ± 4.53	1.72 ± 1.29 (34)	95.46 ± 3.80
TN	#1	18.2 ± 3.1 (40)	17.59 ± 15.73	27.1 ± 3.1 (32)	22.26 ± 10.36	18.5 ± 4.7 (34)	45.21 ± 9.45
	#2	14.2 ± 2.8 (40)	35.21 ± 15.97	21.7 ± 2.2 (32)	37.86 ± 5.87	12.2 ± 3.3 (34)	64.80 ± 5.67
TP	#1	1.22 ± 0.72 (40)	62.45 ± 21.75	2.19 ± 0.59 (32)	66.89 ± 9.47	–	–
	#2	1.01 ± 0.44 (40)	68.35 ± 15.48	1.87 ± 0.49 (32)	71.59 ± 8.05	0.75 ± 0.32 (34)	91.90 ± 4.36
COD	#1	43.2 ± 13.3 (40)	61.71 ± 22.36	54.4 ± 21.9 (32)	81.28 ± 8.95	38.1 ± 7.8 (34)	83.40 ± 1.70
	#2	31.1 ± 11.8 (40)	72.17 ± 15.98	41.5 ± 10.8 (32)	85.68 ± 4.61	32.7 ± 9.4 (34)	89.57 ± 4.10

[a] 

[b]RE: removal efficiency.

[c]The #1 and #2 denote the control tank in the original process and the upgraded tank in the ICEAS process, respectively.

[d]Test times (days).

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Further remarks and economic analysis

The following system security measures were considered. To make carriers move freely and avoid clogging, several strategies were adopted in different operation phases. In the mixing phase, the position and direction of three new mixers were strategically chosen to ensure suspension of the carriers. The impellers with large diameters and low speeds could produce higher flows. In the aeration phase, a simple aeration system with perforated stainless tubes and air spargers was used to provide uniform internal flow dynamics and aeration evenness. Furthermore, after start-up, the water flux through the filter screen would decrease due to the accumulation of impurities like hairs and attached biofilms over time, which eventually caused the carriers to clog in the decanting phase. Therefore, perforated pipes were installed on the bottom of the units in front of the packing screen; in this way, higher shear forces going along with the pumping mechanically accelerated the circulation of carriers and prevented biofilm adhesion to the filter screener. Regular cleaning was also carried out with water cannons. During reactor maintenance, carrier removal and temporary storage for reuse (if not damaged) was required. Thus, mobile latch jacks were fitted to salvage carriers, and filter screens with weep holes were placed on the bottom.

According to statistics in 2008, the real mean treatment flow and power consumption per day were 5.67×10^4 m^3 and 1.45×10^4 kW·h, respectively. Air compressors and influent pumps are the main power consumption equipment. Table S1 (available online at http://www.iwaponline.com/wst/070/370.pdf) theoretically compares the specific electricity power consumptions between original and upgraded biological tanks (in Phase 3). In a cycle for each series, the aeration consumption was decreased by 26.1% due to reduced aeration time, and lower cost of operation could be theoretically achieved with annual electricity power savings of 1.04×10^7 kW·h. This was comparable to recent upgrade costs of the second phase with the step feed process, where the cost reduction was approximately 2.98×10^5 kW·h (Ge *et al*. 2012b).

CONCLUSIONS

The addition of floating carriers, and optimum modifications based on the maximum utilization of the existing ICEAS configuration, were shown to enhance process performance and stability. In particular, the optimization of the operational sequence with real-time control strategies, such as stopping the filling cycle during the aeration process, increased anoxic time instead of oxic time, and the sludge return system, contributed to improved denitrification and nitrification. Besides, the attached biofilms on carriers further guaranteed nitrification, especially in winter, and the aeration system and packing screen helped to resolve the carrier clogging problem. In addition, due to the 26.1% aeration consumption saving in each cycle, the total annual power consumption was reduced by 1.04×10^7 kW·h in theory.

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