Design and operation of an eco-system for municipal wastewater treatment and utilization

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Abstract An eco-system consisting of integrated ponds and constructed wetland systems is employed in Dongying City, Shandong Province for the treatment and utilization of municipal wastewater with design capacity of 100,000 m^3/d. The total capital cost of this system is 680 Yuan (RMB) or US\$82/m^3/d, or about half that of the conventional system based on activated sludge process, and the O/M cost is 0.1 Yuan (RMB) or US\$ 0.012/m^3, only one fifth that of conventional treatment systems. The performance of the wastewater treatment and utilization eco-system is quite good with a final effluent COD, BOD, SS, NH_3-N and TP of 45–65 mg/l, 7–32 mg/l, 12–35 mg/l, 2–13 mg/l and 0.2–1.8 mg/l respectively and the annual average removals of COD, BOD, SS, NH_3-N and TP are 69.1%, 78.3%, 76.4%, 62.1% and 52.9% respectively, which is much better than that of conventional pond system or constructed wetland used separately and illustrates that the artificial and integrated eco-system is more effective and efficient than the simple natural eco-system.

Keywords Constructed wetland; eco-system; hybrid facultative pond; pond system; wastewater

Introduction

All over the world wastewater treatment technology has been improved substantially during the last few decades. However, in several parts of the world, decisions on the more efficient use of the appropriate technologies are often made not on the basis of their general benefits but are dictated by various other factors, which often result in wrong direction and decision and in high cost installation.

The high costs (for construction, maintenance and operation) of the most conventional treatment processes has brought about economic pressures to society even in developed countries, and has forced engineers to search for creative, cost-effective, and environmentally sound ways to control water pollution. One technical approach is to construct artificial ecosystems as a functional part of wastewater treatment and utilization (Wang, 1985, 1987, 1991). In this way not only the wastewater could be reclaimed and reused as a new water resource in agriculture, industry, municipal, domestic and other fields, but the organic and nutrient substances are also transformed and transferred in the food chains of the eco-system, which are finally recovered as resources in form of fish, duck/geese and aquatic plants or vegetables (Wang, 1991; Wang, *et al.*, 1999, 2001).

Pond and wetland systems are widely employed both in developed and developing countries (Oswald, 1995; Pearson, 1996; Hodgson and Paspaliaris, 1996, Wang *et al.*, 1999, 2001; Knight and Kadlec, 2000) for wastewater treatment. In order to further improve the performance of these systems in removing various pollutants and realizing the

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wastewater utilization, the integrated eco-system for wastewater treatment and utilization by combining eco-ponds with constructed wetland has been developed by the authors.

Over 200 days of zero flow in Yellow River that took place in 1997 and then followed by frequent occurrence of no flow cases in this river made Dongying City face severe water shortage, a large area of the existing farmland has been abandoned due to water shortage for irrigation and aquaculture. Therefore, the municipal wastewater has to be reclaimed and reused as a regenerated or renovated water resource. A three years survey was carried out to collect the basic data on climates, wastewater quality and geographic conditions for finding a suitable approach. After a feasibility study on comparison of three different treatment alternatives, the eco-system was select as the final decision. Since this eco-system for wastewater treatment and utilization was commissioned on 1 October 2000, one year's operation has exhibited positive results with good performance.

Material and methods

Description of eco-system site

Dongying City is located at the estuary of Yellow River, where exists the Shengli (Victory) Oil Field, the second largest oil field in China with an annual crude oil production of 32 million tons. The climatic conditions of Dongying City are of the semi-arid continental type, characterized by relatively low precipitation rates with an annual average of 533 mm, and normally concentrated in June through September, longer solar radiation period with an annual average of 2696.5 hours, an intensive evaporation rate of 1897.1–2765.8 mm and high temperature fluctuation from 39.9 °C of the highest temperature to −21.2 °C of the lowest temperature. Furthermore, there is no groundwater available for irrigation, and the only surface water source is the Yellow River.

The designed ecological wastewater treatment and utilization system (EWTUS) in this form has the treatment and utilization flowchart as follows:

Raw wastewater → Screens → Grit Chambers → Hybrid Facultative Ponds → Aeration Ponds → Aerated Fish Ponds → Fish Ponds → Lotus Ponds → Constructed Wetland → Effluent to Guangli River.

The design parameters of the treatment unit

The integrated eco-system was designed according to the National Design Guidelines for Wastewater Treatment Ponds with the consideration of the local climate and geographic conditions, such as the characteristics of soil, where the foundation of the plant would be laid and other impact factors. The eco-system for wastewater treatment and utilization was designed by Design Institute of Architecture and Civil Engineering, Harbin Institute of Technology and finished at the end of 1998; its advanced hybrid facultative pond is a combined one of intensified facultative pond (Qi and Wang, 1993) with advanced facultative pond developed by Oswald (1991), in which the hydraulic retention time was chosen as 1.5 d, the water depth 5 m, and dense package of ringlace shape carriers to 30% of total effective volume with a specific area of 800 m^2/m^3. The hybrid facultative ponds function as main unit ponds for removing suspended solids and organic load while realizing sludge digestion and fermentation without sludge discharge for many years. The design parameters of each treatment unit are shown in Table 1.

Sampling and analysis methods

Wastewater samples were taken at different points of the treatment units along the treatment flowchart. The samples were taken directly by means of 2 L sampling beaker for each two hours. The samples collected at each point were then mixed to form composite

Table 1 Main design parameters of unit ponds of the Eco-system in Dongying

Unit pond	Surface area (Ha)	HR T (d)	Water depth (m)	Remarks
Advanced hybrid facultative pond (AHFP)	3.5	1.5	5	Fermentation pits on the bottom and biofilm carrier packing layer 1 m depth and 0.3 m below water surface
Aerated ponds (AP)	3.5	1.3	3.6	16 surface aerators (2.2 kw)
Aerated Fish ponds (AFP)	29	10.6	3.4	16 surface aerators (2.2 kw) + 8 water fall springs
Fish ponds (FP)	12.2	2.4	2.0	Earth dike with grass cover
Lotus pond (LP)	7.6	0.8	1.0	Earth dike with grass cover
Const. Wetland (CW)	35.2	1.8	0.5	Earth dike with grass cover

samples for 24 hours a day. For bacteriological wastewater analysis, the immediate sample was taken and transported in sterile sample bottles and kept in refrigerator at laboratory for waiting analysis.

The analysis methods were employed in the test is coordinating with the Chinese National Standard Guidelines for operation processes (China NEPA, 1989).

Results and discussion

Characteristics of raw wastewater

The raw wastewater flow of a whole year average entering the wastewater treatment eco-system was in the range of 40,000–50,000 m^3/d, which is far below the designed raw wastewater flow of 100,000 m^3/d because of incomplete municipal wastewater collection or sewerage system in the service area, which also made the raw water quality lower than that of design figures. Table 2 shows both the design quality and actual quality of raw wastewater.

Based on these results shown in Table 2, it is evident that the wastewater treatment plant of Dongying City is well below its normal capacity in terms of both hydraulic load (about 50% below design capacity), and organic load (around 25% below design capacity).

Because the incomplete or partial collection system is a combined system, this made the raw wastewater quality be influenced both by seasons and infiltration of groundwater due to shallow groundwater table, in the range of 0.5–2.5 m, and the lowest point of pipeline of the collection system is normally in the range of 1.5–9 m, thus making raw wastewater diluted significantly through infiltration.

Performance of eco-system

Since the eco-system was commissioned on 1 October 2000, there has been about one year operational study. The performance of the wastewater treatment and utilization eco-system is shown in Figures 1–7, which show the variation of some main parameters along flowchart (as shown in Figure 1) or with operation time (Figures 2–7), from which it is found that the system is significantly influenced by the season, particularly the

Table 2 Raw wastewater qualities in design and actual operation

Parameters	Design quality (mg/l)	Actual quality (mg/l)
BOD_5	100	74.74
COD	250	166.14
SS	100	92.86
NH_3-N	20	23.12
TP	5	2.46

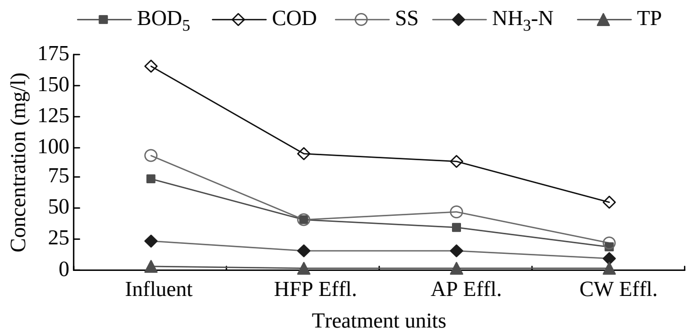

Figure 1 Variation of main parameters along the treatment flowchart

rainfall period from June to October, which made the raw water diluted and the removal efficiency lower, while from January to May, or in dry weather seasons, the raw wastewater was concentrated and was treated with higher efficiency.

The removal efficiencies for some main pollutants in various unit ponds showed that the advanced hybrid facultative ponds play a major role in organic removal with COD and BOD mean removal efficiencies of 42.7% and 44.5% respectively, which are much lower than those of the advanced anaerobic ponds treating high strength piggery wastewater built in Panyu Guangdong Province with COD and BOD removals of 85.7% and 90.4% respectively (Wang *et al.*, 1996). The aerated ponds and aerated fish ponds (see Figure 9) that follow the advanced hybrid facultative ponds also play very important role in further removing organic pollutants with a final Effluent COD and BOD reaching 55

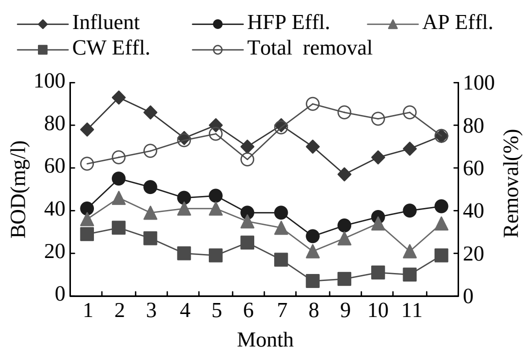

Figure 2 BOD_5 variation with operation time

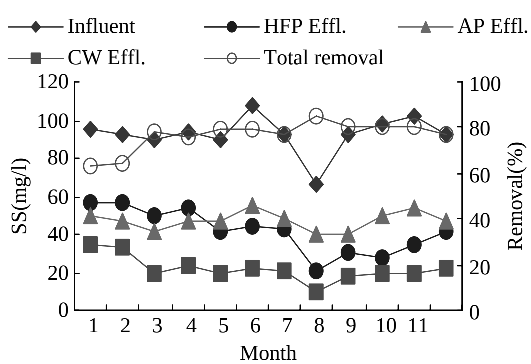

Figure 3 SS variation with operation time

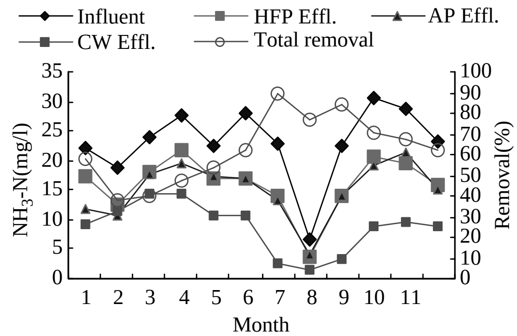

Figure 4 Ammonia variation with operation time

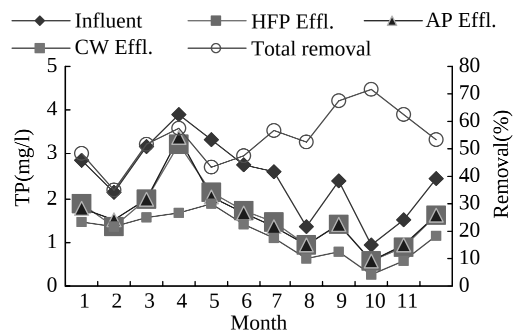

Figure 5 TP variation with operation time

and 20 mg/l or less respectively, as shown in Figure 1. Besides, the heavy metals and some toxic and harmful organic compounds are removed efficiently in the advanced facultative ponds and aeration ponds through various mechanisms, such as the formation of insoluble metals sulfides precipitates and bio-degradation of organic compounds by aerobic, facultative and anaerobic bacteria and fungi, which serve as barriers to prevent heavy metals and toxic organic compounds from entering the food chains.

Special design for the hybrid facultative pond and its performance

As mentioned above the raw wastewater was diluted significantly, particularly in rainy seasons, which makes the system very difficult to operate and maintain, especially in wet climate, the BOD_5 contained in raw wastewater normally being lower than 50 mg/l. Another unsuitable condition is the temperature, as it is well known that the eco-system

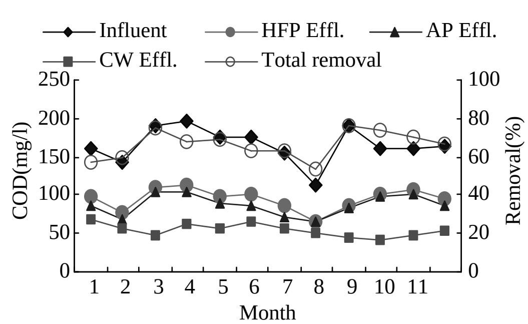

Figure 6 COD variation with operation time

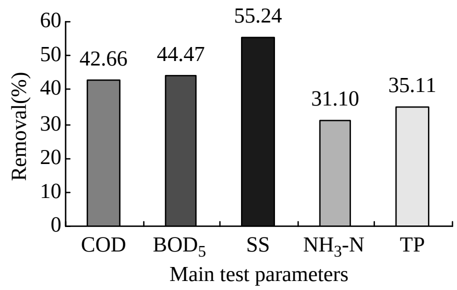

Figure 7 Pollutants removal in the hybrid facultative pond

is very sensitive to temperature. In winter, when the water temperature is lower than 10 °C, the bacteria could not effectively remove the organics and also there are only few aquatic plants living in ponds, then the eco-system performed not very well, even the effluent could not meet the discharge standard. In order to overcome this disadvantage, the special design was employed in the advanced hybrid facultative pond (AHFP), which is shown in Figure 8. The height of water column in the AHFP is 5 m, of which 1 m high of carriers were packed beneath 0.3 m of the water surface for biofilm attached growth and maintaining the sludge digestion in the anaerobic fermentation pits on the bottom. The raw water comes in from the bottom of the anaerobic digestion pits and then flows upwards for providing the close contact between the raw wastewater and anaerobic activated sludge in the lower part and biofilm in the upper part, by which the anaerobic, anoxic and aerobic conditions are formed and the corresponding bacteria and fungi are developed for degradation of larger molecular organic compounds into smaller ones. Another positive aspect of this specially designed pond is that the carriers could keep the temperature not very low in winter and resistant the heat release into the air, and also prevent the odour, such as H_2S and mercaptans from release into the atmosphere, which are removed through bio-degradation by some bacteria in biofilm under aerobic conditions.

Furthermore, it was found in our earlier study that the attached growth biofilm provides favourable living and growing conditions for nitrifier (Wang *et al.*, 1996), which is an available approach to placing biofilm support surfaces in the ponds to create an immobilized nitrifier population. The positive results indicated that all of them achieved surface nitrification rates of at least 30 to 40 mgN/m^2/h. And also according to the experience of combined biofilm/activated sludge system, the biofilm attached on the carrier provide place for nitrifier growth and culture for long life time, the TN removal of this system normally reach 60–70%, which is much higher than the conventional activated sludge system (Wang *et al.*, 1991).

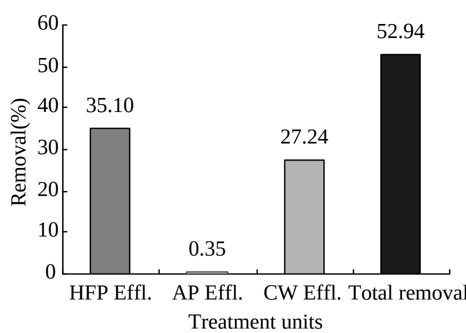

Figure 8 TP removal in different treatment units

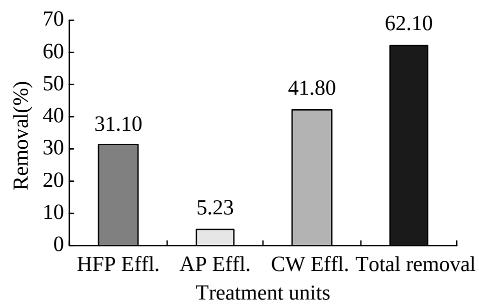

Figure 9 NH_3-N removal in different treatment units

The effectiveness of the advanced hybrid facultative pond in removing organic matter, ammonia and total phosphorus is well illustrated in Figure 7, in which 42.7% of COD removal was achieved with a total COD removal of 69.1% in the system; 44.5% for BOD, with 78.3% of total BOD removal; SS 55.2%, with 76.5% of total removal; NH_3-N 31.1%, with 62.1% of total removal; and for TP 35.1%, with 52.9% of the total removal.

Constructed wetland

As it is well known, the constructed wetland has higher removal efficiency for nutrients with 60% and 70% removal for TN and TP respectively (Shen and Wang, 1999). The plants in the surface flow constructed wetland serve a number of functions. The submerged stems serve as media for attached growth of biofilm including bacteria, fungi, algae, protozoa and metazoa. The leaves above the water surface shade the water from sunshine and reduce the potential for algal growth. Oxygen is transported from the leaves and surface water column in the wetland from re-aeration to the root zone, which supports the plants' growth.

The surface water flow wetland system employed in this eco-system covers a total area of 35.2 ha, with HRT of 1.8 days and water depth of 0.6 m, in which the reed was grown as treatment plants, which is very efficient in pollutants removal. The performance of the constructed wetland is shown in Figures 8 and 9, in which TP and TN were removed by 27.24% and 41.8% respectively, which nearly accounted for 51.45% of total TP removal and 67.43% of total ammonia removal in the whole system respectively.

Capital and O/M costs

The total capital cost of this project is 68 million Yuan (RMB), or US$ 8.2 million, and the unit capital cost is 680 Yuan or US$ 82 per m^3/d, which is about 1/3–1/2 that of conventional treatment plant based on activated sludge process.

The unit operation/maintenance (O/M) cost is only 0.1 Yuan/m^3 or US$ 0.012/m^3.

Conclusion

The integrated and comprehensive eco-system is employed in Dongying City, Shandong Province for municipal wastewater treatment and utilization, which involves advanced hybrid facultative pond (AHFP), aeration pond (AP), fishing pond (FP), lotus pond (now changed to a duckweed pond (DP) because of poor growth of lotus) and constructed wetland (CW). Fixed biofilm carriers were assembled inside of the AHFP to provide place for attached growth of bacteria and algae on the surface for improvement of the pond performance, and positive results were achieved in the first year operation with 43% of COD removal, 44% BOD, 35% TP, 32% NH_3-N and 35% TP.

The performance of total eco-system is very good with a final effluent COD, BOD, SS, NH_3-N and TP reaching 45–65 mg/l, 7–32 mg/l, 12–35 mg/l, 2–13 mg/l and 0.2–1.8 mg/l. respectively and the annual average removal of COD, BOD, SS, NH_3-N and TP are 69.1%, 78.3%, 76.4%, 62.1% and 52.9% respectively, which is much better than that of conventional pond system or constructed wetland used separately and illustrated that the comprehensive eco-system is more effective than the simple natural system.

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