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Multi-stage ponds-wetlands ecosystem for effective wastewater treatment*

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Abstract: The performance of the Dongying multi-stage ponds-wetlands ecosystem was investigated in this work. Study of the removal of different pollutants (BOD_5, COD, SS, TP, TN, NH_3-N, etc.) in different temperature seasons and different units in this system indicated that effluent BOD_5 and SS were constant to less than 11 mg/L and 14 mg/L throughout the experimental processes; but that the removal efficiencies of pollutants such as TP, TN, NH_3-N, COD varied greatly with season. The higher the temperature was, the higher was the observed removal in this system. Additionally, each unit of the system functioned differently in removing pollutants. BOD_5 and SS were mainly removed in the first three units (hybrid facultative ponds, aeration ponds and aerated fish ponds), whereas nitrogen and phosphates were mainly removed in hydrophyte ponds and constructed reed wetlands. The multi-stage ponds-wetlands ecosystem exhibits good potential of removing different pollutants, and the effluent quality meet several standards for wastewater reuse.

Key words: Multi-stage ponds, Wetland, Ecosystem, Temperature, Performance
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INTRODUCTION

Pond systems are commonly employed for municipal sewage purification, especially in developing countries, due to its cost-effectiveness and high potential of removing different pollutants. Unfortunately, algae would bloom in the ponds and cause secondary pollution of the following stream. To tackle this problem, several methods combining both ponds and filtering system had been tried (Christian *et al.*, 2003). Dongying multi-stage ponds-wetlands ecosystem was designed embodying these ideas.

Built on the basis of traditional stabilization pond and wetland technology, the Dongying multi-stage ponds-wetlands ecosystem possesses many advantages. Firstly, this system is composed of several eco-ponds and wetlands in certain proportion and fashion, basing on the ecosystem concept. Secondly, this system has several functions: wastewater treatment, water reclamation and reuse, nutrient recovery and recycling, and so on (Steinmann *et al.*, 2003; Wang *et al.*, 2001); furthermore, it was easily and conveniently operated, and possessed stable and high efficiency for pollutants removal. Therefore, it is especially suitable for developing countries such as China.

To obtain valuable data for further operation and design, it is necessary to thoroughly investigate this system's performance, which is the objective of this study. Parameters such as BOD_5, COD, SS, nitrogen and phosphorous in each unit of this system were carefully determined from January, 2001 to December, 2003. Additionally, effects of temperature

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on different pollutants removal in different units were also studied.

STUDY SITE DESCRIPTION

The multi-stage ponds-wetlands system in Dongying City (37.5° N, 118.5° E) was designed on the basis of artificial eco-system consisting of a wide variety of food chains through fish farming and aquatic plant growth. This kind system can substantially improve the performance, and assure high removal efficiency for various pollutants while water is being reused and recycled.

In addition to some pretreating units such as screening and grit chambering, the Dongying multi-stage ponds-wetlands system comprises two main parts (Fig.1): one is the ponds system, including hybrid facultative ponds (HFPs), aeration ponds (APs), aerated fish ponds (AFPs), fish ponds (FPs) and hydrophyte ponds (HPs); the other is the constructed reed wetlands (CWs) system. The physical and hydraulic characteristics of this system are given in Table 1.

The hybrid facultative pond is a new type primary facultative pond having the advantages of two kinds of primary facultative ponds, which were respectively developed by Green *et al*.(1996) and Wang *et al*.(2001). The hybrid facultative pond is comprised of sludge fermentation pits and a kind of intensified pond with much more biomass in the form of suspension or attached growth on the carrier. Wastewater flows zigzag due to the introduction of baffles, which assured that pollutants in the wastewater could fully contact the bio-film attached on the carrier and sludge deposited on the bottom.

MATERIALS AND METHODS

Water samples were collected 2–3 times a week. DO and pH were measured in situ with a Hach model 16046 portable dissolved oxygen meter and an Inventron pH/mV meter fitted with a combined pH electrode, respectively. Original water samples were immediately sent to laboratory and passed through a 2 mm sieve to remove large suspended solids such as duckweed. Then the sub-samples were separately filtered through Whatman GF/F 0.70 μm filter paper to determine the dissolved components and through the Millipore APFF 0.70 μm filters to determine the particulate component.

NH_3-N, total nitrogen (TN), NO_3^--N, NO_2^--N and total phosphate (TP), dissolved total phosphate (DTP), BOD_5, dissolved BOD_5 ($DBOD_5$) were analyzed following standard methods (APHA, 1995).

RESULTS AND DISCUSSION

Temperature has impact on pollutants removal in ecological system (Green *et al.*, 1995). Therefore,

Table 1 Physical and hydraulic characteristics of this system

Stages	Dimension ($L\times B\times H$) (m^3)	Designed flow (m^3/d)	HRT* (d)	pH
HFPs	138.9×65.9×5	25000×4	1.46	7.6–8.0
APs	133.4×66.3×3.6	25000×4	1.29	7.6–8.2
AFPs	866.6×275×3.5	100000	8.30	7.7–9.0
FPs-I	800×100×2.0	65000	2.40	8.1–9.1
FPs-II	400×126×2.0	35000	2.40	7.9–9.0
HPs	800×95×1.0	100000	0.76	8.4–9.1
CWs	390×227×0.4	50000×2	0.90	7.5–8.2

*HRT: Hydraulic retention time

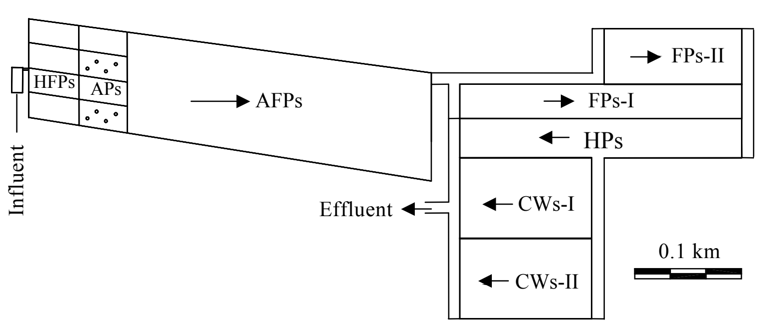

Fig.1 Layout of multi-stages ponds-wetland system in Dongying City
HFPs: hybrid facultative ponds; APs: aeration ponds; AFPs: aerated fish ponds; FPs: fish ponds; HPs: hydrophyte ponds; CWs: constructed reed wetlands

the removal efficiency of different pollutants was separately considered under cold (<10 °C) and warm (>20 °C) seasons in this study.

BOD_5 removal

1. Comparison of BOD_5 removal in different seasons and different units

Fig.2 shows that BOD_5 removal variation in cold season was generally less than that in warm season. For example, in cold season, the removal efficiency of BOD_5 was about 84.5%, whereas in warm season, that increased to 91.8%, with the final effluent BOD_5 below 11 mg/L and 6 mg/L respectively. These variations may be due to different bio-activity of microbes with temperature. In cold season, the metabolism and bio-activity of microbes were rather low; whereas, with the temperature increasing, the biomasses and activities of microbes increased at high speed, which resulted in higher BOD_5 removal (Steinmann *et al.*, 2003).

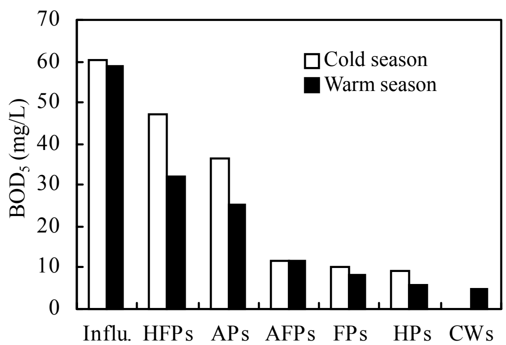

Fig.2 BOD_5 variation in different temperatures

Fig.2 indicates also that more than 80% of BOD_5 was removed in the first three units (hybrid facultative ponds, aeration ponds and aerated fish ponds). Additionally, the effluent BOD_5 of AFPs ranged from 8 mg/L–13 mg/L in different seasons, exhibiting constant capability of removing BOD_5. These results demonstrated high potential of removing BOD_5 by the first three units, especially AFPs.

2. BOD_5, $DBOD_5$ and $SBOD_5$ removal

BOD_5 is comprised of dissolved BOD_5 ($DBOD_5$) and suspended BOD_5 ($SBOD_5$). Obviously, $SBOD_5=BOD_5-DBOD_5$. $R_{DBOD/BOD}$ (ratio of $DBOD_5$ to BOD_5) represents variation of BOD_5 composition. Fig.3 of the variation of BOD_5, $DBOD_5$ and $SBOD_5$ in different units shows that tend to decrease while flowing through the system. Furthermore, it was observed that $R_{DBOD/BOD}$ first decreased and then increased; and that $SBOD_5$ content was minor in the effluent BOD_5.

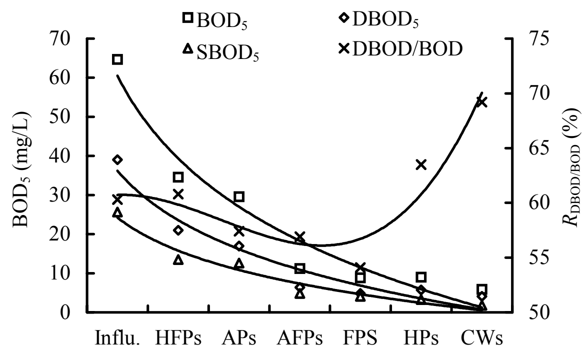

Fig.3 BOD_5, $DBOD_5$, $SBOD_5$ and $R_{DBOD/BOD}$ variations trends in different units

The decrease of $SBOD_5$ was mainly due to sedimentation and microbe decomposition. Organic particulates sedimentation was the main factor in $SBOD_5$ removal in front units; whereas microbe decomposition played an important role in $SBOD_5$ removal in latter units. This kind of microbe decomposition led to decrease of $SBOD_5$ and increase of $DBOD_5$ (Chris *et al.*, 1998), which were the causative reasons for $R_{DBOD/BOD}$ variation in this system. It was noteworthy that $R_{DBOD/BOD}$ in the CWs effluent was rather higher than other units, demonstrating that CWs can effectively remove suspended organic matters.

3. Model of BOD_5 removal in HFPs

A model was developed for prediction of transformation and removal of BOD_5 in the new type hybrid facultative pond. It was hypothesized that BOD_5 removal of HFPs satisfied the BOD_5 removal model of Eq.(1) (Aloice, 1996).

$$\frac{S_e}{S_o}=\frac{1}{1+K\cdot t} \tag{1}$$

where, S_e (mg/L) is effluent BOD_5 and S_o (mg/L) is influent BOD_5 of HFPs; t (d) is the hydraulic retention time and K (d^{-1}) the first-order removal rate constant for BOD_5.

Fig.4 presents the relation between calculated K in Eq.(1) and water temperature in 2003. Consequently, simulative K' can be calculated from the results in Fig.4:

$$K'=0.0668\times e^{0.1375T} \quad (r^2=0.8946) \tag{2}$$

where, T (°C) is the mean water temperature of HFPs.

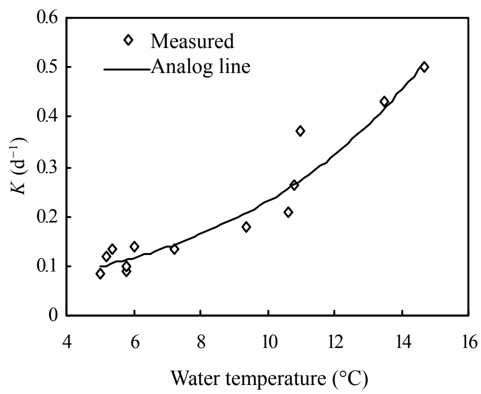

Fig.4 *K* variations with the water temperature

From the results listed above, BOD_5 removal in HFPs was as follows:

$$S_e = \frac{S_o}{1+0.0668e^{0.1375T}t} \tag{3}$$

Fig.5 shows the results of BOD_5 predicted by the model and measured values from HFPs in 2002. Linear regression analysis of the relation on the model and measured BOD_5 has shown a good agreement with a slightly low coefficient of regression (r^2) of 0.76. Such agreement of the model data with actual 2002 data indicated that simulative K' was valid for use in the formulation of the model describing the removal processes of BOD_5.

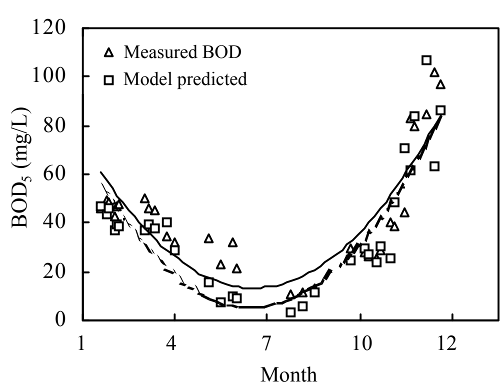

Fig.5 Measured and predicted BOD_5 of HFPs

COD removal

COD removal was lower than that of BOD_5 in pond and wetland systems (Schetrite and Racault, 1995). Fig.6 of COD removal variation in different units shows that COD removal of HFPs, APs and AFPs ranged from 14% to 26% and was higher than those of other units (<10%). Actually, these three units contributed to more than 61% of COD removal. Fig.6 shows also that seasonal variations had significant potential effect on COD removal. In warm season, the removal efficiency for COD was 73% and greater than that in cold season (40%). Actually, final effluent COD in warm season was 32 mg/L–48 mg/L; whereas in cold season, it was as much as 65 mg/L–74 mg/L.

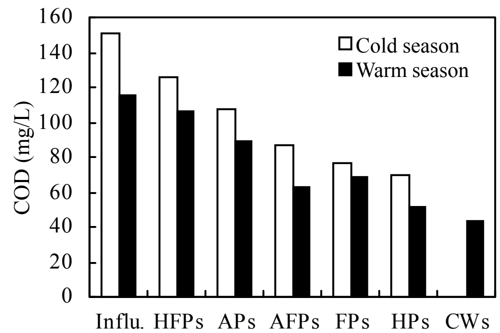

Fig.6 COD variation in different temperatures

Suspended solid removal

Suspended solids (SS) in multi-stage ecosystem showed different characteristics, so the mechanisms involved in SS removal were complex (Krishnappan, 1999).

Fig.7 shows that more than 70% of SS was removed in the first two units in both warm and cold

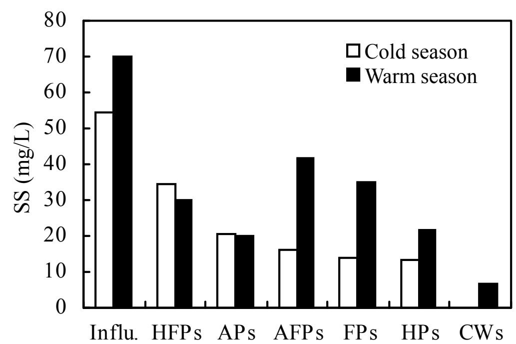

Fig.7 TSS variations in different temperatures

season and that SS of APs effluent was constantly about 20 mg/L. The good performance of SS removal may be due to the higher proportion of large-sized and easily settled particulates contained in influent SS.

On the other hand, the overgrowth of algae would therefore substantially change the characteristics of SS removal in this system. Fig.7 compares SS removal between cold and warm season, showing that SS in warm season was higher than that in cold season for such units as AFPs, FPs and so on. In cold season, hydrophyte and hydrofauna contributed less to SS increase and the effluent SS was steadily between 10.3 mg/L and 14.0 mg/L. In warm season, however, hydrophyte and hydrofauna grew overwhelmingly and subsequently led to high SS of as much as 43 mg/L in AFPs. Fortunately, effects of fish and zooplankton consumption, algae self-settlement, roots filtration of reeds and duckweeds and so on in the following units could further lead to substantial SS reduction (Nozaily-Al *et al.*, 2000), ensuring that the final SS will be mostly less than 9.5 mg/L.

The mechanisms involved in SS variation in this system were complex. Compared to ordinary pond system, this multi-stage system may effectively reduce the adverse effect of algae over-reproduction and ensure effluent quality.

Nitrogen removal

Organic nitrogen and ammonia nitrogen (NH_3-N) were main nitrogen types in wastewater. Organic nitrogen is usually converted into NH_3-N under both aerobic and anaerobic conditions. Therefore, NH_3-N removal mainly contributed to total nitrogen (TN) removal. Three main processes involved in NH_3-N removal were: hydrophytes uptake, volatilization and nitrification/denitrification (Sommer and Olesen, 2000).

Biological nitrification/denitrification was a most important factor in NH_3-N removal. In multi-stage ecosystem, however, this effect did not play an important role in NH_3-N removal (Maynard, 1999). Actually, results of this study showed that NO_3^--N and NO_2^--N were steadily less than 0.8 mg/L in 95% of samples (data not presented). The lack of sufficient surface area for attachment of bacteria may be one of the reasons for the weak nitrification/denitrification effect in this system. Actually, Muttamara and Puetpaiboon (1996) reported higher NH_3-N removal with increasing surface area for bio-film attachment by carriers.

Temperature and pH had impact on the bioactivity and volatilization and therefore on NH_3-N removal in this system. Fig.8 compares NH_3-N removal between cold and warm season, showing that only 19.6% of NH_3-N was removed in cold season; but in warm season, as much as 71.4% was removed. In warm season, hydrophytes grew more overwhelmingly and therefore consumed more NH_3-N for metabolism. Simultaneously, more CO_2 was consumed during photosynthesis and resulted in higher pH (ranged from 8.5 to 9.1) during daytime, which led to higher NH_3-N volatilization rate. Furthermore, higher temperature itself facilitated more volatilization. The effects listed above were the causative factors for the higher NH_3-N removal in warm season. In cold season, however, bio-assimilation and physical volatilization were inhibited and therefore NH_3-N removal was very low.

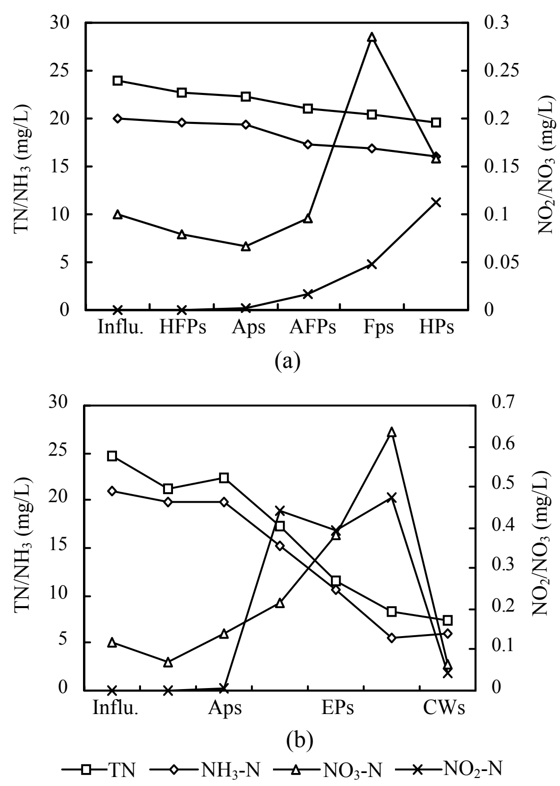

Fig.8 Comparison of nitrogen concentrations in different units (a) Cold season; (b) Warm season

Additionally, though the content of ammonia in FPs was more than 10 mg/L throughout most of 2003, the growth of the cultured fishes showed satisfactory results, with survival rate ranging from 40% to 60% in harvesting time. It may be due to the selected fish breeds (such as common carp) with high resistance to ammonia. Further experiments on the effect of ammonia on fishes are ongoing at present.

Phosphates removal

In pond system, adsorption of phosphates to sedimentary particles is an important removal process. The adsorption capacity is mainly dependent on the presence of Fe^{3+}, Ca^{2+} or Al^{3+} in sediments (Verhoeven and Arthur, 1999). Additionally, phosphates can also be precipitated with Fe^{3+}, Ca^{2+} or Al^{3+} contained in wastewater. The uptake of plant was also reviewed as one important removal pathway of phosphates, but it only plays some role in the growing season.

Fig.9 compares phosphate removal in different seasons and different units. As indicated in Fig.9, significantly higher removal efficiencies of AFPs, FPs and HPs were observed in warm season than that in cold season. TP removal of AFPs, FPs and HPs was constant and less than 10% in cold season, reaching 13%–35% in warm season, especially from September to October. This could be due mainly to the adsorption of sediment, because the content of total phosphates in sediments exhibited significant increase from July to November, as revealed by sedimentary phosphates measurement (Emil, 2000; Arauzo *et al.*, 2000). Fig.9 shows that temperature had no significant effects on TP removal in the first three ponds. Actually, TP removal efficiencies of these units were constantly 7%–15% throughout the experiment processes. It could be due to the precipitation rate and adsorption rate being constant with temperature (Robert and William, 2000).

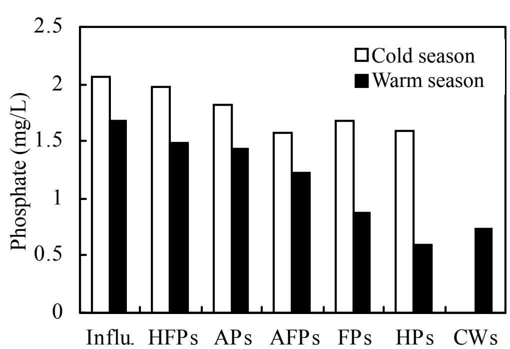

Fig.9 TP variation in different temperatures

To further investigate phosphates removal in this system, different type phosphates reduction was studied (Fig.10). It was observed that the ratio of dissolved phosphates to TP decreased from 95% to 81% in the first three ponds, indicating that soluble phosphates was partly transformed to insoluble phosphates by microorganism assimilation. From AFPs to CWs, however, the ratio increased from 81% to 99%. This was due to the effects of algae consumption by fish and zooplankton in this system and the filtration of the roots of duckweed and reeds. These results indicated that the system had much effect on insoluble phosphates removal.

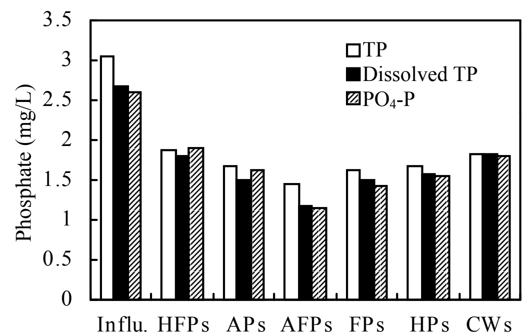

Fig.10 Different phosphates variations in system (April)

CONCLUSION

From the results listed above, main conclusions may be stated as follows:

1. The Dongying multi-stage ponds-wetlands system showed good potential for removing COD, BOD_5 and SS. Nitrogen and phosphates were thoroughly well removed in warm season; in cold season, as low as 25% of TN and TP were removed in this system;

2. Several mechanisms were usually involved in this system for every pollutant removal, and the dominant mechanism differed greatly between different ponds and different seasons.

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