Efficiencies of residual organic pollutants removal from secondary effluent by switching of coagulation–air flotation–filtration processes

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Abstract It is an essential task to remove the residual organic pollutants (ROP) from secondary effluent of a Wastewater Treatment Plant (WWTP) in wastewater reclamation and reuse processes. Four different compared flow schemes would be achieved for further purification of the secondary effluent by switching of different valves. In order to mainly remove non-biodegradable residual organic pollutants under various operating conditions, the optimum technology and economic process was obtained in the advanced purification flow scheme at a flow of 3200 m^3/d in Harbin Wenchang WWTP. Conclusions under a lot of experiments show that: choosing the coagulation-settler plus biofilm filter for advanced purification process is reasonable; during the stable operation phase, this process showed good performance in removing the COD, BOD_5, TP, NH_3-N and SS; the removal rates are 50%, 39%, 67%, 50%, 80% respectively. The effluent is able to excel the requirements for wastewater reuse standards. The unit cost of the water is 0.542 yuan/m^3, which is far below the fee paid for supply water, long-distance transfer water or seawater desalination through economic analysis.

Keywords Air flotation; biofilm filter; coagulation; residual organic pollutants; wastewater reclamation and reuse

Introduction

With the largest population in the world, China has a very limited per capita water capability and uneven spatial and temporal water resource distributions (SEPA, 1999). It is reported that more than half of the 667 cities in China are facing water shortage (He *et al.*, 2001). What's more, industrialization and urbanization have accelerated pollution in the water environment (Christova-Boal *et al.*, 1996), making water a limited resource, especially in northern China, and thus great attention is being paid to the reclamation and reuse of treated water discharged from municipal or industrial wastewater treatment plants (WWTPs) (Croce *et al.*, 1996; Aramaki *et al.* 2001; Eriksson *et al.*, 2002; Fane *et al.* 2002). Advanced/tertiary plays a critical role in the effective treatment of municipal and industrial wastewater to meet water quality objectives for water reuse and to protect public health. Conventional wastewater treatment consist of a combination of physical, chemical, and biological processes and operations to remove settleable, suspended, and dissolved solids, organic matter, metals, nutrients, and pathogens from wastewater. However, existing conventional treatment facilities that consist of primary treatment, biological treatment, and clarification processes have some limitations in removing the non-biodegradable portions of organic matter, fine colloids, and dissolved inorganic species and thereby they were not able to meet the requirements for wastewater reuse standards (Choo and Kang, 2003).

In the Harbin area, nearly 500,000 m^3 of wastewater was produced per day, which after its simple primary treatment is being discharged into the Songhua River without any further secondary or tertiary treatment before the year 2000. The Songhua River is the source of the water supply in Harbin area, which is extremely deficient in water. During

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the dry season, an upstream reservoir has to discharge from its storage, which is accumulated in the wet season to ease the water shortage in this area. Along with the water shortage, the pollution of the water environment (especially after the 2005 nitrobenzene episode) is another problem confronting Harbin. The local government and municipal environmental protection agency have registered serious concern at wasting a valuable potential resource—and propose reclaiming wastewater. A thorough survey and negotiation was under way from 1996 to 1999, and wastewater reclamation and reuse was finally considered as the most appropriate option for the Harbin area. It was not until 2000 that a full scale wastewater treatment plant (WWTP), named as "Harbin Wenchang Wastewater Treatment Plant", was established at Taiping district, far from the downtown city. The Wenchang WWTP with a capital cost of 384 million yuans (1 U.S. $\$ = 8.1$ yuan) which consisted of an aerated grit chamber plus an conventional Anaerobic/Oxic (A/O) biological treatment process followed by advanced treatment process (Figure 1 shows the detail processes of the plant) has been put into operation successfully for about two years.

Wastewater with a flow of 325,000 m^3/d for primary treatment and only 160,000 m^3/d for secondary treatment is treated; about half of the influent wastewater is discharged directly into the Songhua River without secondary clarification for some reason, and about 4000 m^3/d of the secondary treated effluent is pumped to the tertiary treatment procedure for reuse in washing the machine, clearing the road, and flushing flowers and grass, etc. Disinfection is often the final treatment step before storage and distribution. The Wenchang WWTP is the first wastewater treatment plant in Harbin. It is a historic breakthrough for wastewater disposal in the Harbin after its successful construction and stable operation. Under the established of the project, the drainage wastewater from Majia Ditch community was treated mostly, and it has a significant role in integration of treatment of Majia Ditch, releasing the overloaded discharge of the organic pollution into the Songhua River, improving the comfortable living environment of Harbin, boosting the citizen living quality, and then promoting the sustainable development of economics in Harbin.

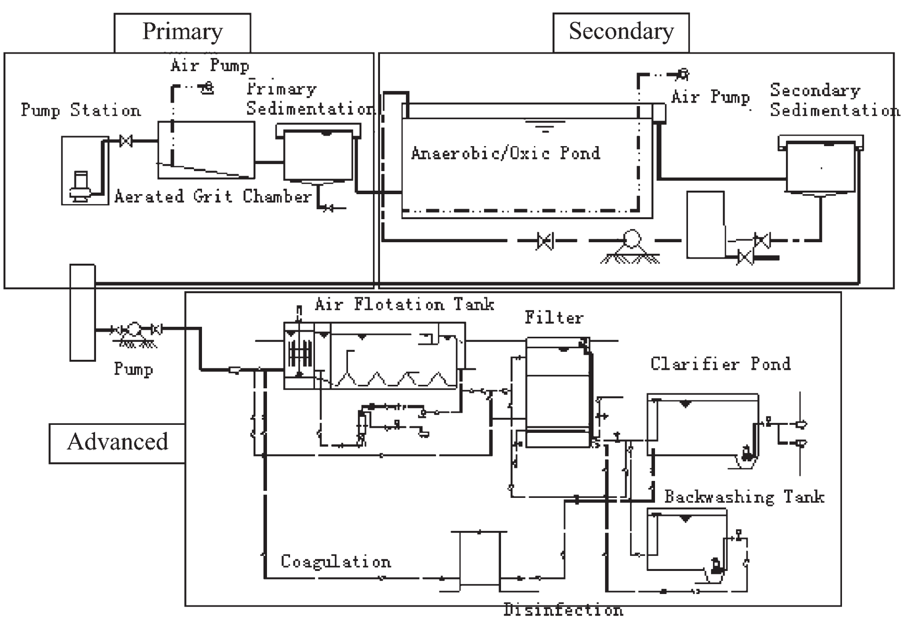

Figure 1 Conventional secondary wastewater treatment and advanced clarification in Harbin Wenchang WWTP

Materials and methods

The framework of wastewater reuse system

In this project, an indoor full-scale advanced treatment workroom was established near the discharge channel of secondary sedimentation. The flow scheme of 3200 m^3/d advanced treatment process is shown in Figure 2, which includes two chemical coagulation tanks with mixer, two air-flotation ponds, and four filters (including two BAFs and two fast-filters). The detailed parameters of each treatment unit is shown in Table 1.

There are four filters in the workroom, and two of them are pumped with the air, the other two flow with treated water directly without air supply. The debug strategy of the Wenchang advanced treatment aims at the following four compared flow processes by switching the valves in the workroom.

Flow 1: secondary effluent + filter (and BAF)

Flow 2: secondary effluent + chemical coagulation + filter (and BAF)

Flow 3: secondary effluent + air flotation + filter (and BAF)

Flow 4: secondary effluent + chemical coagulation + air flotation + filter (and BAF)

The experiments carry on in the order of the flow above in order not to affect the next flow process. The former process served for the next one and hence achieved the overall goal of the completed flow process (Flow 4). Finally the optimum option of the processes was obtained, especially in the economic and technology aspects.

Sample of the water and methods

The water samples were taken from the effluent of each unit, which included secondary effluent, the outflow of coagulation, air-flotation, and the filters. There are two sample points for the filter of effluent, one is the biological aerated filter; the other is the effluent of the fast filter. The water quality parameters were detected each day. Feed wastewater (secondary effluent) and treated water samples were analysed for biological oxygen demand (BOD), COD, ammonia nitrogen (NH_3-N), UV absorbance, and other parameter as displayed in Table 2. The methods and guidelines on water quality are shown in Table 3 below.

Results and discussions

The startup of the tertiary treatment

The startup of the advanced treatment process was mainly dependent on the startup of the BAF, which was relying on the activities of nitrification. Nitrification activity was measured as ammonia nitrogen removal rate per unit biomass. The experiment was carried out in the BAF where the air was supplied to give a high DO level of about 5 mg/L at the startup stage. Samples from influent, effluent-1 (without oxygen), and effluent-2

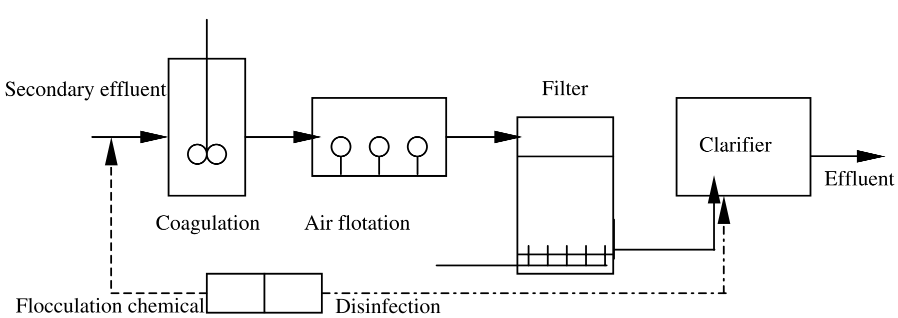

Figure 2 Flow scheme of 3200 m^3/d advanced treatment process

Table 1 Detail parameter of treatment unit

Treatment unit	Size (L × W × H)/m	Total Volume/m^3	HRT/min
Coagulation Tank	3.6 × 2.45 × 2.7	23.8	26
Air flotation	7.7 × 3.9 × 3.0	90	98
Filter	3.8 × 2.2 × 4.2	35	38
Backwash tank	12.6 × 3.85 × 3.5	170	–
Water storage tank	12.6 × 2.85 × 4.3	150	–

Table 2 Characteristics of secondary effluent

Parameter	Range of value	Average
NH_3-N, mg/L	0.5 ~ 19	11
PO_3-P, mg/L	1.5 ~ 4	3
COD, mg/L	25 ~ 96	68
BOD, mg/L	15 ~ 35	25
SS, mg/L	4 ~ 31	11
DO, mg/L	1.5 ~ 7	4.5
NO_3-N, mg/L	12 ~ 20	16.9
NO_2-N, mg/L	0.036 ~ 0.31	0.107
Turbidity,NTU	1 ~ 7	3.0
pH	6 ~ 9	7.25
UV_{254}	0.15 ~ 0.25	0.198

Table 3 Methods and guidelines of water quality

Parameter	Method
Clour	National standard
Turbidity	HACH turbidity machine
DO	HACH DO instrument
pH	HACH pH glass electrode
BOD_5	Dilution and inoculation
COD_{Cr}	Digestion
SS	103 °C ~ 105 °C daying weight
Total-P	Ascorbic acid methods
NH_3-N	Nessler
Nitrate	Cadmium reduction
Nitrite	Hydroxybenzene sulphur

(with oxygen) were taken to determine the nitrification activity; the detailed value of each sample and the corresponding removal rate are showed in Figure 3.

Figure 3 summarizes the different nitrification activity of the two kinds of filter (one is supplied with air, the other with no air supply). From the figure we can clearly see that the removal rate of ammonia nitrogen in BAF is better than the fast filter under the conditions of small influent flux. The smaller the flux, the less the hydraulic shear, and the longer the contacted time between the nitration bacteria and stuff material. Comparing effluent-1 (E1) and effluent-2 (E2), we can calculate that the ammonia nitrogen removal rate of E2 reaches 23.8% after its 11 days incubation, and arrives at a stable state of 30% after about half a month. At this point, the start-up of the advanced treatment is over.

The COD removal efficiency in the four flows

After about one month start-up of the system, mainly focusing on the start-up of the BAF, we can say that the BAF has reached its stable phase. Experiments of the removal

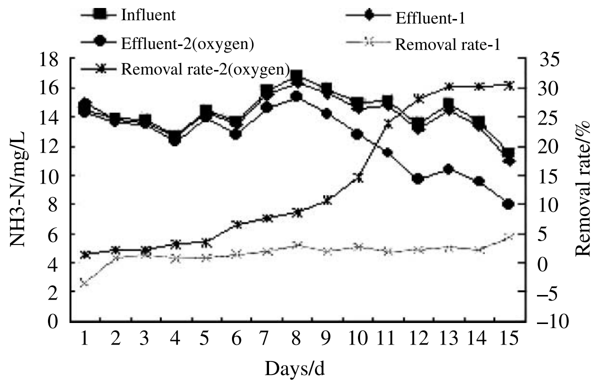

Figure 3 Ammonia nitrogen removal rate at the startup

efficiency were carried out under the steady phase. The COD variation and the total COD removal efficiency of each flow are shown in Figures 4 and 5.

All in all, the average value of COD influent was about 50 ~ 60 mg/L, and the effluent of each flow can meet the requirements of water reuse standards. From Figure 4 we can see that the COD decreases step by step from each unit building, and the BAF enhances the total COD removal efficiency of effluent with the air supply. After the advanced treatment, the aerobic effluent COD of the four flows decrease to 29.4 mg/L, 29.8 mg/L, 32 mg/L and 28 mg/L, and the effluent of fast filter without air supply is 39 mg/L, 40 mg/L, 44 mg/L and 37.7 mg/L. Figure 5 shows that the total E1 COD

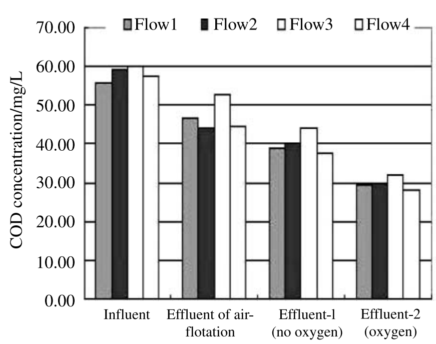

Figure 4 COD variation of each flow

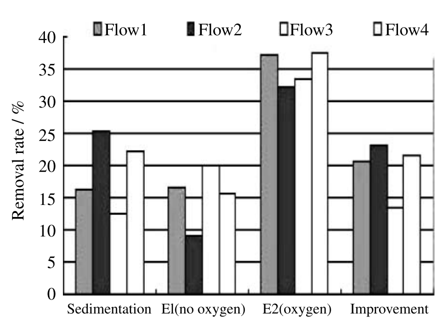

Figure 5 Total COD removal efficiency of each flow

removal rates of each flow are 30.1%, 32.2%, 26.7% and 34.4% respectively; for E2 they are 47.3%, 49.5%, 46.7% and 51.2%, so the improvement removal rate of the aerated filter was about 17.2%, 17.3%, 20.0% and 16.8% for flow 1 to flow 4. From Figures 4 and 5 we can see the general removal efficiency of the four flows, but from Figure 5 we know about how the COD removal works in each unit building. The figure tells us that coagulation settling process has enhanced the COD removal efficiency to a certainty. Flow 2 and 4, which the chemical coagulation reagent was added, show good performance in COD removal compared with flow 1 and 3, which had no chemical reagent input. The air flotation has little efficiency in COD removal.

The BOD_5 removal efficiency in the four flows

The detection of BOD_5 was carried out once a week, Table 4 shows the removal efficiency of BOD_5 during a period of time at the stable operation phase.

The data in Table 4 shows that the BAF has better BOD_5 removal rate than the fast filter under a couple of day's cultivation. The BAF can grow kinds of microorganism that can subdue some parts of the non-biodegradable portions of organic pollutants, and the improvement rate of BAF reaches 28.5% at the most. The average BOD of secondary effluent is 14.81 mg/L, and the effluent of the fast filter is 11.94 mg/L; the removal rate of E1 is 19.39%; the effluent of BAF is better than the fast filter and its removal rate is high, up to 39.15%; the improvement rate is 19.76%. The feasibility of secondary effluent wastewater reclamation and reuse is verified by the utility of the biofilm filter technology.

The NH_3-N removal efficiency in the four flows

The nitrification activities of the fast filter and BAF are totally different. The hydraulic load of the filter is low [about 3.0 $m^3/(m^2{\cdot}h)$]. A comparatively long SRT and low hydraulic load could maintain nitrifying bacteria very effectively resulting in giving a comparable nitrification rate. The NH_3-N variation and the total NH_3-N removal efficiency of each Flow are shown in Figures 6 and 7.

From Figures 6 and 7, the ammonia nitrogen removal efficiency of the fast filter is low, but the BAF has different removal performance under different ammonia load of influent. In the high ammonia load of Flows 1 and 3, the average NH_3-N concentration of secondary effluent is higher, up to 15.5 mg/L, but the effluent of BAF is lower than 10 mg/L, which shows the resisting impact load of BAF. We also found that the air flotation process (Flows 2 and 4) shows good assistance for ammonia removal in the fast

Table 4 The removal efficiency of BOD_5

	Influent	Fast filter	BAF	Removal rate of E1	Removal rate of E2	Improvement
1	16.48	14.67	9.98	10.98	39.44	28.46
2	8.68	7.89	8.64	9.10	0.46	− 8.64
3	6.21	6.39	6.65	− 2.90	− 7.09	− 4.19
4	9.62	6.58	4.64	31.60	51.77	20.17
5	11.88	9.34	7.25	21.38	38.97	17.59
6	11.09	9.25	6.94	16.59	37.42	20.83
7	15.17	12.59	9.48	17.01	37.51	20.50
8	19.03	14.56	9.89	23.49	48.03	24.54
9	24.5	19.6	14.8	20.00	39.59	19.59
10	26	20.8	14.0	20.00	46.15	26.15
11	14.8	11.7	8.25	20.95	44.26	23.31
12	15.21	11.34	8.96	25.44	41.09	15.65
12	13.87	10.5	7.68	24.30	44.63	20.33
Average	14.81	11.94	9.01	19.39	39.15	19.76

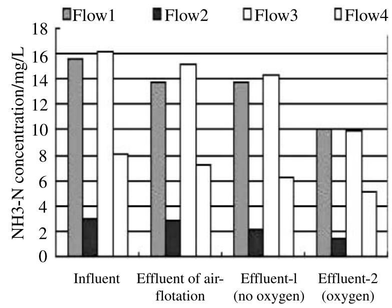

Figure 6 NH_3-N variation of each flow

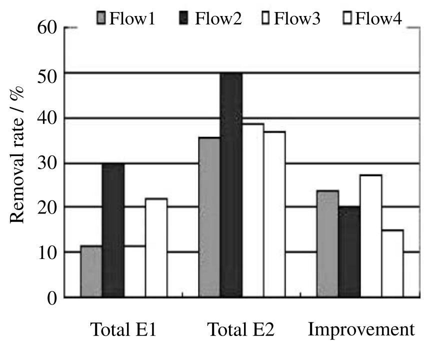

Figure 7 Total NH_3-N removal efficiency of each flow

filter, but the ammonia removal was mainly done in the BAF, and the NH_3-N removal improvement rates of each Flow in BAF are 23.9% (Flow 1), 20% (Flow 2), 27% (Flow 3) and 15% (Flow 4).

The TP removal efficiency in the four flows

Biological phosphorus removal from wastewater is based on the activity of phosphorus accumulating organisms (PAOs). PAOs can release the ortho-phosphate to liquid by taking up the organic carbon substrates in the anaerobic and take up more than is released during the anaerobic phase in the aerobic phase. Because the environment of anaerobic/aerobic conversion cannot be formed at the filter, the total phosphorus removal rate is low in the advanced treatment process without coagulation reagent addition. The P-removal was based on the basic needs of microorganism metabolism. The total phosphorus removal of each unit building is show in Table 5.

Table 5 summarized the TP removal efficiency. As we can seen from the table, Flow 1 and 3 show bad performance at phosphorus removal. The amount of P-removal was about 0.2 mg/L, which was considered as the assimilation of microorganism, and the interception of the filter. The removal of Flow 2 and 4 is comparatively high; the TP

Table 5 The total phosphorus removal efficiency of each flow

Total-P	Secondary effluent	Effluent of air-flotation	Effluent1	Effluent 2(with oxygen supply)
Flow 1	2.3	2.2	2.13	2.02
Flow 2	3	1.12	1.0	0.97
Flow 3	2.6	2.55	2.5	2.43
Flow 4	2.32	1.05	0.95	0.89

concentration is within 1 mg/L. The removal efficiency of each unit building can be seen in Figure 8 below.

As can be seen from Figure 8, the total phosphorus removal rates of Flows 2 and 4 (with chemical reagent addition) was absolutely higher than the other two (without chemical addition), and the removal rates of Flows 2 and 4 was higher up to 67% and 61%; the effluent TP concentration was lower at 1 mg/L. The removal efficiency depends on the amount of coagulation reagent and the TP concentration of the influent.

The SS removal efficiency in the four flows

Figure 9 shows more detail about the SS removal efficiency of each unit building. The SS removal efficiency was studied during the stable phase. The data is shown in Table 6 below.

Figure 9 tells us that the utility of the air-flotation process and coagulation can do well in SS removal. The removal rate decreases step by step from Flow 1 to Flow 4 in the sedimentation. The fast filter shows a more stable performance at SS removal than the aerated filter. The agitation of the air and the rinsing and chafing of the material in the BAF are the two main reasons. From Table 6 above, we can see that the SS concentration of the secondary effluent is not very high. It would be easy to intercept the SS after the purification of each flow. The effluent can meet the requirements of water reclamation and reuse standards easily.

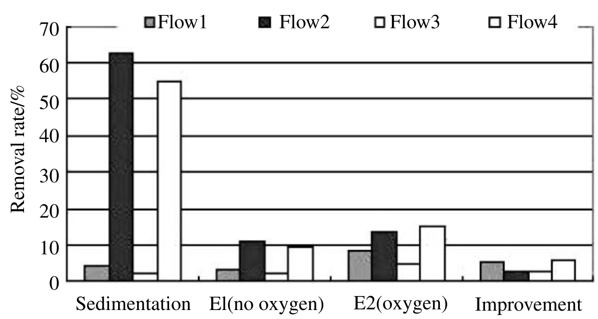

Figure 8 TP removal efficiency of each unit building

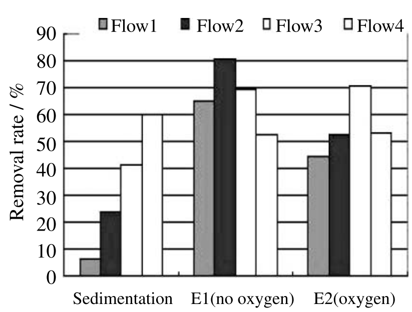

Figure 9 SS removal efficiency of each unit building

Table 6 SS removal efficiency of each flow

SS/mg/L	Secondary effluent	Air-flotation	Effluent 1	Effluent 2
Flow 1	9.2	8.6	3	4.8
Flow 2	10.2	7.8	1.5	3.7
Flow 3	12.7	7.5	2.3	2.2
Flow 4	10.5	4.2	2	1.97

Table 7 The cost estimation of every flow

Item/10^4yuan	Flow 1	Flow 2	Flow 3	Flow 4
Facility investment	135.13	162.79	166.14	193.80
Construction fee	152.23	165.78	203.48	217.03
Facility installation fee	13.51	16.28	16.61	19.38
Permanent assets	300.87	344.85	386.23	430.21
Debugging fee	5.75	6.57	7.39	8.22
Electricity cost/year	13.62	14.79	16.58	17.76
Wage and welfare/year	6	6	6	6
Chemical fee/year	0.38	17.9	0.38	17.9
Depreciation fee/year	14.08	16.38	17.86	20.15
Fixing fee/year	2.11	2.41	2.70	3.01
Daily maintenance fee/year	3.01	3.45	3.86	4.30
Else fee/year	1.96	2.40	2.37	2.81
Total cost/year	41.16	50.40	49.77	59.01
Unit cost (yuan/m^3)	0.352	0.542	0.426	0.616

Note: The plant produces 3200 m^3 reclamation and reuse water per day. Facility installation Fee = Facility investment × 10%; Debugging Fee = (Facility investment + Construction Fee) × 2%; Wage and welfare = 1000 yuan/(month·person) × 12 months × 5people = 6 × 10^4 yuan /year; Chemical Fee = Coagulation reagent Fee + Disinfection Fee; Depreciation Fee = Construction Fee /30 + Facility investment /15; Fixing Fee = Permanent assets × 0.7%; daily maintenance fee = Permanent assets × 1%; Else Fee = (Electricity cost + Chemical Fee + Wage and welfare + Depreciation Fee + Fixing Fee + Daily maintenance fee) × 5%; Total cost = Electricity cost + Chemical Fee + Wage and welfare + Depreciation Fee + Fixing Fee + Daily maintenance fee + Else Fee

Table 8 Comparison of different water treatment processes

Item (yuan/m^3)	Intermediated water	Tap waters	Seawater Desalination	Long-distant transfer
Unit cost	0.35 ~ 0.62	2.3 ~ 4.4	5.0 ~ 6.5	4.0 ~ 5.5

Economic assessment and analysis

Wastewater advanced treatment of secondary effluent is a promising alternative in arid or water shortage areas. The unit cost of the study at Harbin Wenchang wastewater treatment plant was between 0.35 and 0.62 yuan per cubic metre (from Table 7). It is much lower than tap water, seawater desalination and water long-distant transfer (from Table 8). By selling the intermediated water, not only economic benefits but also the environment advantages would be gained.

Conclusions

Coagulation-air flotation-filtration processes were used for further treatment of secondary effluent in order to remove residual organic pollutants and to produce high quality water that is appropriate for reclamation and reuse in the Harbin Wenchang wastewater treatment plant. The result were summarized as below.

- Choosing the coagulation-settler plus biofilm filter as the advanced purification process at a flow of 3200 m^3/d in Harbin Wenchang WWTP is reasonable. The effluent can meet the requirements for wastewater reuse standards.
- During the stable operation phase, this process showed good performance in removing the COD, BOD_5, TP, NH_3-N and SS, the removal rates are 50%, 39%, 67%, 50% and 80% respectively.
- The unit cost of the water is 0.542 yuan/m^3, which is far below the fee paid for supply water, long-distance transfer water or seawater desalination through economic analysis.

The advanced wastewater treatment process of this paper can provide scientific design and technical data for the future design and construction of a full-scale treatment plant.

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References

Aramaki, T., Sugimoto, R., Hanaki, K. and Matsuo, T. (2001). Evaluation of appropriate system for reclaimed wastewater reuse in each area of Tokyo using GIS-based water balance model. *Water Sci. Technol.*, **43**(5), 301–308.

Christova-Boal, D., Eden, R.E. and McFarlanc, S. (1996). An investigation into greywater reuse for urban residential properties. *Desalination*, **106**, 391–397.

Croce, H., Pollara, P., Oliveri, R., Torregrossa, M.V., Valentino, L. and Candura, R. (1996). Operational efficiency of a pilot plant for wastewater reuse. *Water Sci. Technol.*, **33**(10), 443–450.

Eriksson, E., Auffarth, K., Henze, M. and Ledin, A. (2002). Characteristics of grey wastewater. *Urban Water*, **4**, 85–104.

Fane, S.A., Ashbolt, N.J. and White, S.B. (2002). Decentralised urban water reuse: the implications of system scale for cost and pathogen risk. *Water Sci. Technol.*, **46**(6–7), 281–288.

He, P.J., Phan, L., Gu, G.W. and Hervouet, G. (2001). Reclaimed municipal wastewater—a potential water resource in China. *Water Sci. Technol.*, **43**(10), 51–58.

Choo, K.-H. and Kang, S.-K. (2003). Removal of residual organic matter from secondary effluent by iron oxides adsorption. *Desalination*, **154**, 139–146.

SEPA (1999). *China's 1999 Environment Yearbook*, China Environmental Science Press, Beijing, [in Chinese].