Enhanced physicochemical-biological sewage treatment process in cold regions

Guoren Xu, Chao Jia, Zhao Zhang and Yunlong Jiang

ABSTRACT

Biological treatment processes give relatively poor pollutant removal efficiencies in cold regions because microbial activity is inhibited at low temperatures. We developed an enhanced physicochemical-biological wastewater treatment process that involves micro-membrane filtration, anaerobic biofilter, and aerobic biofilter to improve the pollutant removal efficiencies that can be achieved under cold conditions. Full-scale experiments using the process were carried out in the northeast of China, at outdoor temperatures of around $-30\,^{\circ}$C. The average removal efficiencies achieved for chemical oxygen demand, total phosphorus, ammonia nitrogen, and suspended solids were 89.8, 92.9, 94.3, and 95.8%, respectively, using a polyaluminium chloride dosage of 50 mg L^{-1}. We concluded that the process is effective to treat sewage in cold regions.

Key words | cold conditions, micro-membrane filtration, physicochemical-biological, sewage treatment

Guoren Xu (corresponding author)
Chao Jia
Zhao Zhang
Yunlong Jiang
State Key Laboratory of Urban Water Resource and Environment,
Harbin Institute of Technology,
P.O Box 2602,
73 Huanghe Road,
Nangang District,
150090, Harbin,
China
E-mail: *xgr@hit.edu.cn*

INTRODUCTION

The efficiency of a microbial sewage treatment process is greatly affected by microbial activity. Temperature strongly affects microbial growth and activity, so it directly affects the efficiency of a sewage treatment process. Microbial activity in a microbial sewage treatment process will decrease when the water temperature is below 15 °C, and becomes very low when the temperature is less than 10 °C. The microbes will show almost no physiological activity when the temperature is lower than 4 °C (Verstraete & Philips 1998). Low temperatures in microbial sewage treatment processes not only affect microbial activity, but also strongly influence adsorption and sedimentation processes, the compositions of microbial film populations, and the total oxygen transfer efficiencies in biological aerated filters. When the starting temperature is low, microbial activity can double when the temperature increases by around 10 °C (Tsang *et al.* 2007).

A great deal of research has been conducted on sewage treatment processes in cold regions, and sewage treatment plants commonly include processes to overcome the problems caused by low temperatures to ensure that the effluent meets the required discharge standards. Such process methods include decreasing the sewage load, increasing the recycling flow rate and hydraulic retention time, using heat preservation measures, or dosing with hardy bacteria. Ben *et al.* (2009) analysed and identified the components of flora in a domestic sewage treatment system at 4 °C over a long period. They used immobilized psychrotrophs to treat wastewater containing different carbon distributions, and the chemical oxygen demand (COD) in the effluent was found to meet the relevant emission standard. An experimental study of the effectiveness of using mixed psychrotrophs to treat domestic sewage at low temperatures showed that cold-resistant strains were more stable and adaptable than single strains when the temperature of the domestic sewage was 5 °C. The COD removal efficiency in the winter was greatly enhanced when mixed psychrotrophic flora were pulsed into a biological aerated filter used to treat domestic sewage at a low temperature (Chevalier *et al.* 2003). Wang (2007) conducted a pilot study using bacteria with a low temperature tolerance in a biological aerated filter to treat low temperature domestic sewage; and the COD, ammonia nitrogen ($\mathrm{NH_4^+}$–N), and total phosphorus (TP) removal efficiencies peaked at 88.31, 83.1, and 38%, respectively, at a hydraulic load of about $1.6\,\mathrm{m^3/(m^2\,h)}$. Head & Oleszkiewicz (2004) showed that nitrification achieved a positive effect when domesticated nitrifying bacteria were added to a sequencing batch reactor at low temperatures. However, most

doi: 10.2166/wst.2014.376

methods for improving the performance of a sewage treatment process at low temperatures will increase the capital and operational costs involved, and it is difficult to guarantee their sewage treatment efficiency.

The temperature of sewage in treatment plants in northern China is very low in the winter. As mentioned earlier, the biological activity decreases as the temperature decreases, so the effectiveness of sewage treatment processes is lower in the winter than at other times of the year. This causes major problems in the treatment of domestic sewage using traditional biological treatment processes. In the study presented here, enhanced physicochemical treatment by coagulation and micro-membrane filtration was used to develop an enhanced physicochemical-biological sewage treatment process for treating sewage in the northeast of China.

MATERIALS AND METHODS

Enhanced physicochemical-biological sewage treatment process

A primary strengthening treatment was performed using a micro-membrane filtration device (see Text S1 in the supplementary information (SI), available online at http://www.iwaponline.com/wst/070/376.pdf), and the device was connected to a secondary biological treatment system, which included a secondary anaerobic biofilter and a third stage aerobic biofilter. Municipal sewage was passed through a coarse screen before the coagulant was added, and then it was transferred into the primary micro-membrane filtration and integrated sludge treatment device. The effluent was then passed through a two-stage biofilter (see Text S2 in SI, available online at http://www.iwaponline.com/wst/070/376.pdf). A flowchart illustrating the stages involved in the enhanced physicochemical-biological sewage treatment process is shown in Figure 1. The micro-membrane was made of composite polymer materials with a pore size of 210 μm. The anaerobic and aerobic biofilters were each contained in a 7 × 7 × 7 m unit in a reinforced concrete structure. Each biofilter contained a 4 m depth of lava filtering materials, and the wastewater flowed upwards through the biofilters.

Process parameters for the full-scale sewage treatment plant experiments

Full-scale experiments using the enhanced physicochemical-biological sewage treatment process were carried out at a sewage treatment plant in the northeast of China (around 44° N) between December 2012 and February 2013, and the outdoor temperature was around $-30\,^{\circ}$C. The plant was built as a full-scale enhanced physicochemical-biological sewage treatment process demonstration project. The system was designed to be capable of treating wastewater influent containing 200–500 mg L^{-1} COD, 150–500 mg L^{-1} suspended solids (SS), 3–8 mg L^{-1} TP, 40–70 mg L^{-1} total nitrogen (TN), and 20–60 mg L^{-1} NH_4^+–N. The plant had a treatment capacity of 10,000 $m^3\ d^{-1}$, and the capacity will be increased to 20,000 $m^3\ d^{-1}$ in the future.

Once the sewage had been dosed with the coagulant and mixed, it was filtered using three micro-membrane filtration devices (two being used, and one present as a

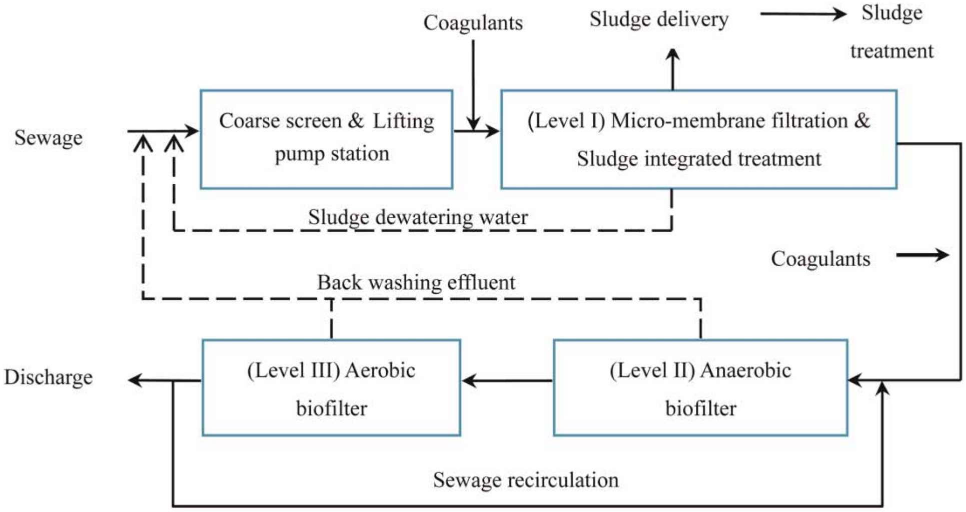

Figure 1 | Flowchart of the processes involved in the sewage treatment plant.

backup) and then transferred to the secondary anaerobic biofilters along with sewage backflow from the third stage aerobic biofilters. The sewage was treated using the anaerobic biofilters and then the aerobic biofilters. The sewage was aerated to allow the organic pollutants to be oxidized, and a nitration reaction generated nitrite and nitrate from the NH_4^+–N.

Two secondary anaerobic biofilters were used in the experiments, and each had a capacity of 833.33 $m^3\,h^{-1}$, a flow rate of 10.29 $m\,h^{-1}$, a volume load expressed in terms of NO_3–N of 1.66 $kg\,m^{-3}\,d^{-1}$, a hydraulic retention time of 38 min, and a reflux ratio of 100%. Four aerobic biofilters were also used, and each had a capacity of 833.33 $m^3\,h^{-1}$, a filtration rate of 5.15 $m\,h^{-1}$, a volume load of $f_{NH_4^+-N} = 0.5$ kg NH_4^+–N $m^{-3}\,d^{-1}$, $f_{BOD} = 1.54$ kg $BOD_5\,m^{-3}\,d^{-1}$, and a hydraulic retention time of 76 min.

Methods for analysing water quality and biofilm formation

Water samples were collected once each day from sampling points on the inlet and outlet pipes of the structures in which each treatment occurred, and the samples were analysed for SS, COD, TP, and NH_4^+–N within 1 h of being collected. The methods used to determine the water quality were based on Chinese Environmental Protection Agency standard methods (State Environmental Protection Administration of China 2002b). The analytical methods and equipment used are listed in Table 1. Biofilm formation on the lava filtration materials was characterized using scanning electron microscopy (SEM) analysis (Sathananthan & Nottola 2007).

Table 1 | Analytical methods and equipment used to test water quality

Analyte	Analytical method	Analyte	Analytical method
SS	Gravimetric method	TP	Antimony molybdenum spectrophotometry
COD	Potassium dichromate method	NH_4^+–N	Nessler's reagent colourimetric method
DO	Portable DO instrument (OXi3310; WTW, Weilheim, Germany)		

RESULTS AND DISCUSSION

Operational parameter selection for the enhanced physicochemical-biological sewage treatment process

Determination of coagulant dosing parameters

The optimum coagulant dosage and dosing method were determined at the pre-operation stage so that the operating parameters used in the sewage treatment plant were fully optimized. The effectiveness of chemical coagulation, flocculation, and precipitation in raw wastewater (Hsu 1976; Thomas *et al.* 1996; Galarneau & Gehr 1997; Clark & Stephenson 1999; Aguilar *et al.* 2002; Franceschi *et al.* 2002; Ebeling *et al.* 2003; Wang *et al.* 2005; Yan *et al.* 2006; Tsang *et al.* 2007) were investigated concomitantly with the practical situation of the wastewater treatment plant before the coagulant was chosen. Polyaluminium chloride (PAC) was selected as the appropriate coagulant because of its low treatment cost, strong adsorption capacity, good solubility, applicability to a wide range of pH values, low corrosion to equipment and pipes, and because it performs better in a purification capacity than other inorganic flocculants. In particular, the PAC can still achieve stable coagulation efficiency when operating at low temperatures, it is effective in removing phosphorus, and is widely used in the northern areas of China for wastewater treatment. We undertook jar tests with PAC (using sewage with a pH of about 7.5) at dosages of 10–70 $mg\,L^{-1}$ to find the optimum dosage (Figure S1 in SI, available online at http://www.iwaponline.com/wst/070/376.pdf). The pollutant removal efficiencies were very good when a PAC concentration of 50 $mg\,L^{-1}$ was used. The removal efficiencies were not obviously improved when the coagulant dosage was increased further, so a PAC concentration of 50 $mg\,L^{-1}$ was selected for use in the demonstration sewage treatment plant.

Determination of dissolved oxygen (DO) in the secondary biological treatment units

Operational data from using biofilters have shown that, in general, the DO concentration should be at least 2 $mg\,L^{-1}$ to ensure that the microorganisms survive the aerobic biofiltration stage (Bicudo *et al.* 2000). However, nitrification and the removal of organic matter require a DO concentration in the main liquid zone of at least 3 $mg\,L^{-1}$ for processes that include microbial attachment

(Farabegoli *et al.* 2009) because of the surface area of the attached microbes and the DO requirements of the heterotrophic bacteria and nitrifying bacteria biofilms. This ensures that there are sufficient nitro-bacteria in the biofilm to complete the nitrification process and ensures that the DO can penetrate the biofilm. The DO concentration in the aerobic biofilter was therefore maintained at between 3 and 4 mg L^{-1}.

Performance of the enhanced physicochemical-biological sewage treatment process

The main purpose of the full-scale experiment was to examine the performance of the enhanced physicochemical-biological sewage treatment process at low temperatures. The tests that were performed included comparing the pollutant removal efficiencies achieved with and without dosing the system with a coagulant. The secondary anaerobic biofilter hydraulic retention time was 38 min, and the anaerobic filtration reflux ratio was 200%. The third aerobic biofilter hydraulic retention time was about 76 min, and the DO concentration was maintained at between 3 and 4 mg L^{-1}.

Pollutant removal efficiencies achieved by primary micro-membrane filtration

Total suspended solids (TSS), COD, and TP removal efficiencies achieved using micro-membrane filtration with and without adding coagulant are shown in Figure 2. The TSS removal efficiencies were approximately 60% without coagulant dosing, and 80% with coagulant dosing; COD removal efficiencies were approximately 25% without coagulant dosing, and about 45% with coagulant dosing; TP removal efficiencies were approximately 4% without coagulant dosing, and about 95% with coagulant dosing. This shows that adding PAC to the wastewater greatly increased the ability of the micro-membrane filtration device to remove TSS, COD, and TP.

The main principle involved in removing pollutants from sewage using a micro-membrane filtration device is that the surface of the filtration membrane has dense micron pores that can form a sludge blanket composed of pollutants, which increases the filtration effect along with continuous filtration of the sewage. This causes SS particles in the water to be retained by the film on the micro-membrane filtration device and the TSS in the sewage to be greatly decreased. As the SS are removed from the

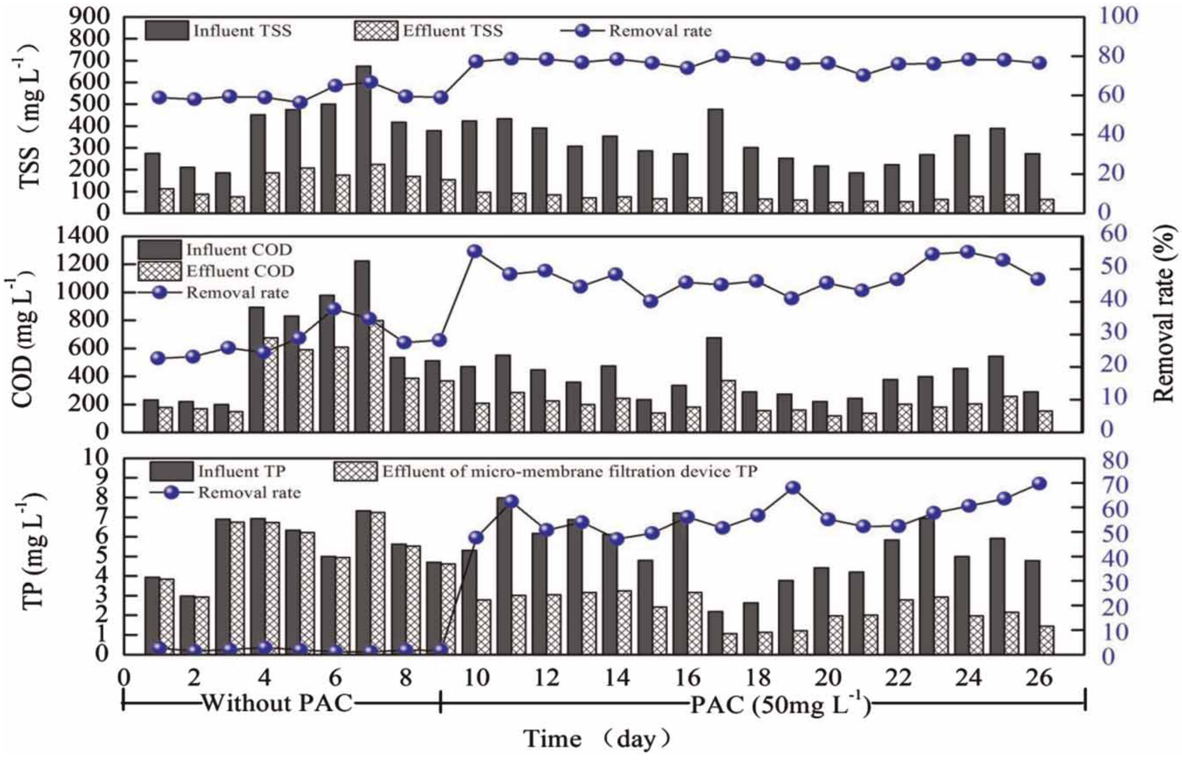

Figure 2 | TSS, COD and TP removal efficiencies with micro-membrane filtration device.

sewage, many insoluble and high molecular weight organic contaminants are also removed, greatly decreasing the COD in the effluent.

Pollutant removal efficiencies achieved using the secondary anaerobic biofilter

The COD and TP removal efficiencies achieved in the secondary anaerobic biofilter stage are shown in Figure 3. The COD in the effluent was partially removed in the secondary anaerobic biofilter stage, and the removal rate was around 20%. The NH_4^+–N concentration in the effluent was increased because of the biological decomposition of organic nitrogen during the secondary filtration stage. Only small amounts of TP were removed from the effluent in the secondary anaerobic biofilter stage, and the removal rate was around 1.5%.

Pollutant removal efficiencies achieved using the third stage aerobic biofilter

The COD, TP, and NH_4^+–N removal efficiencies achieved in the aerobic biofilter are shown in Figure 4. The COD concentration in the effluent was lower than 50 mg L^{-1} and the NH_4^+–N concentration was lower than 8.0 mg L^{-1} once the system had reached a stable operational state. The effluent water quality met the national grade A standard defined in the 'discharge standards of pollutants for municipal wastewater treatment plant' (GB18918) (State Environmental Protection Administration of China 2002a).

The biofilms grew rapidly and the heterotrophic bacteria and nitrifying bacteria competed for DO during the initial phase of the treatment process, providing that the substrate concentration was sufficiently high. This inhibited the growth of nitrifying bacteria and decreased the nitrification rate. In addition, the nitrate content in the reflux liquid was low, and the NH_4^+–N removal rate was reasonably low. The nitrification rate and the NH_4^+–N removal rate both increased as the amount of nitrifying bacteria present increased (Pogue & Gilbridge 2007). We measured the NH_4^+–N concentration throughout the full-scale experiments (Figure S2 in SI, available online at http://www.iwaponline.com/wst/070/376.pdf).

Two types of phosphorus absorption by the microorganisms could have occurred when coagulant was not added to the system. One of these types is normalized absorption, resulting from the physiological needs of the growing microorganisms (Mino *et al.* 1998) and the other type is enhanced biological phosphorus removal by polyphosphate accumulating bacteria that absorb phosphorus to sustain their growth or to store phosphorus through the phosphatic mode (Oehmen *et al.* 2007; Zhang *et al.* 2013). These phosphorus absorption mechanisms would have resulted in

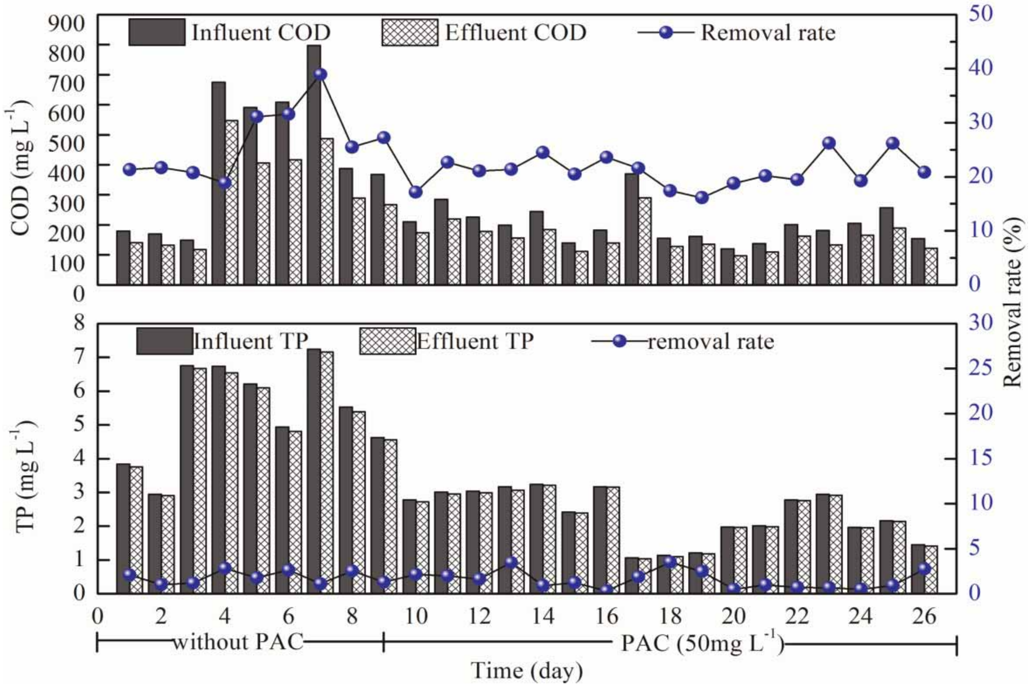

Figure 3 | COD and TP removal efficiencies achieved using the secondary anaerobic biofilter stage.

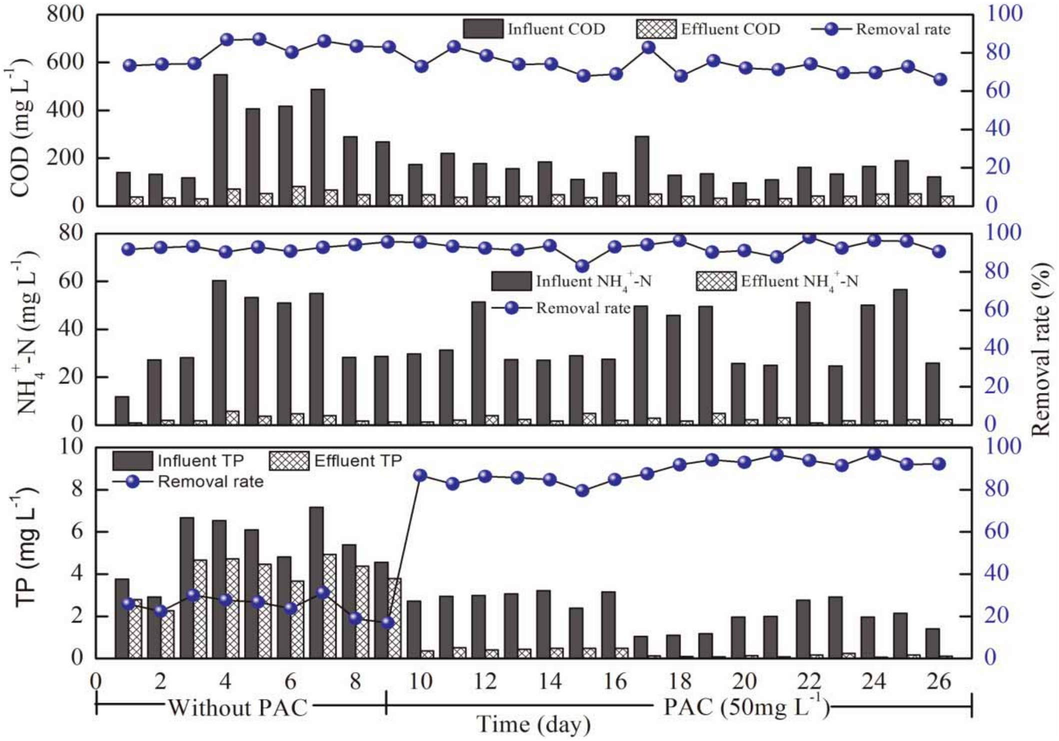

Figure 4 | COD, NH_4^+–N and TP removal efficiencies achieved in the third aerobic biofilter stage.

sludge with a high phosphorus content being formed, and this sludge was discharged from the treatment system, removing phosphorus. Biological phosphorus removal is not ideal, so the strict discharge standards that are set mean that it needs to be supplemented by chemically enhanced phosphorus removal (see Text S3 in SI, available online at http://www.iwaponline.com/wst/070/376.pdf).

Pollutant removal efficiencies achieved using the enhanced physicochemical-biological sewage treatment process

The pollutant removal efficiencies achieved with and without adding PAC were tested in our experiments (Figure 5). Without adding PAC, the average COD removal rate was 89.8%, the average NH_4^+–N removal rate was 94.3%, the average TSS removal rate was 95.8%, and the average TP removal rate was 27.5%. The average TP removal rate was 92.9% when PAC was added.

The process using micro-filtration enhanced by the physicochemical treatment with 50 mg L^{-1} PAC under cold conditions efficiently removed TSS, COD, and TP. The filtration membrane surface had dense micrometre-sized pores and could retain most of the SS in the wastewater. At the same time, a sludge blanket layer composed of TSS from the sewage, which strengthened and increased the TSS and COD removal efficiency, formed on the filtration membrane surface (see Text S4 in SI, available online at http://www.iwaponline.com/wst/070/376.pdf). Adding the coagulant also played a role in the chemically enhanced coagulation process by increasing the amount of colloids removed from the particulate pollutants and improving the removal efficiency in the subsequent processing unit (Amirtharajah & O'Melia 1991; Adin & Asano 1998). The biofilm attached to the surface of the lava filtration material also removed soluble COD because of biological filtration interception and adsorption. After the organic pollutants had been absorbed, some of the COD pollutants were removed from the biological filtration material via retaining and biological adsorption.

Biofilm formation on the lava filtration material when operating in winter

The sewage plant worked well when it was operated in the winter, and the effluent quality met the national grade A standard of the 'discharge standards of pollutants for municipal wastewater treatment plant' (GB18918) (State Environmental Protection Administration of China 2002a). We took the lava filtration material from the secondary anaerobic biofilter and third stage aerobic biofilter and

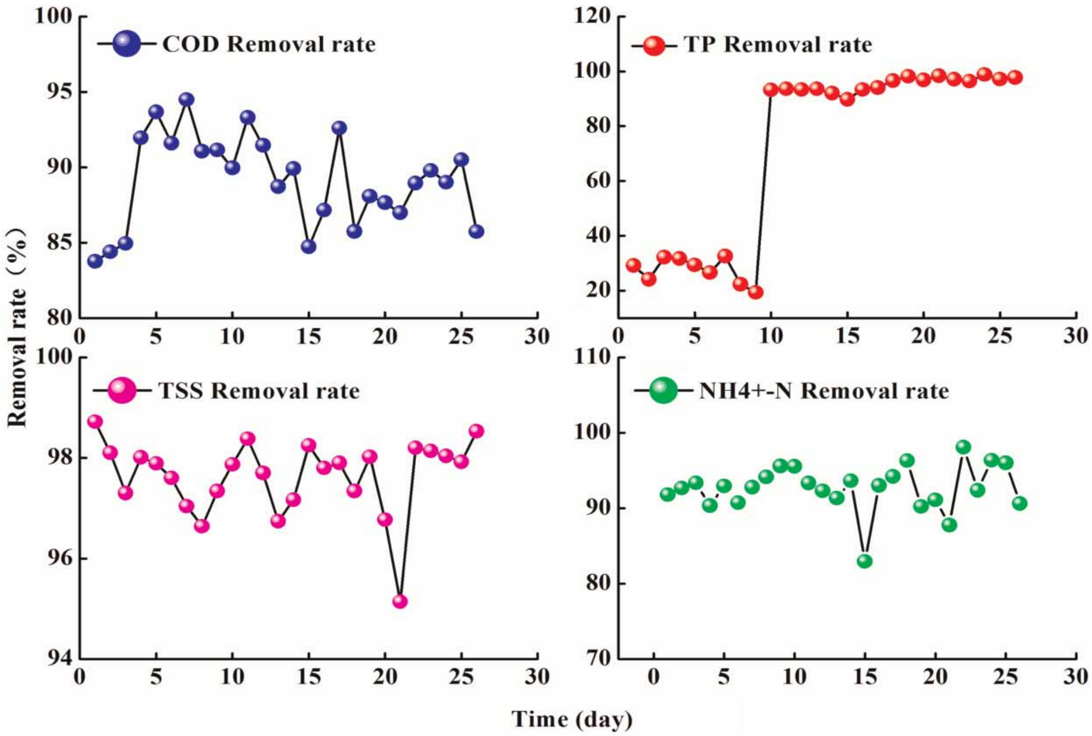

Figure 5 | Removal efficiencies achieved using the enhanced physicochemical-biological sewage treatment process with and without PAC dosing; days 1–9 without PAC, days 10–26 with PAC added (50 mg L^{-1}).

inspected the material using SEM in an attempt to gain a better understanding of microbial growth in the filtration tanks when the influent was at a low temperature. We found that the biofilm on the filtration material was well formed (Figure 6). At the same time, we monitored the temperature of each of the sewage treatment units when they were operating in the winter.

The sewage plant was located in northeast China, where the minimum winter temperature can reach −40 °C. The full-scale experiments were performed in the winter, and the outdoor temperature during the experiments was −23 °C to −38 °C. The temperatures of the sewage treatment units during the experiments are shown in Figure 7. The water temperature in the biological treatment units remained stable at around 10 °C, which was favourable for the growth of microorganisms. The whole process took place in a compact, single structure, which minimized heat loss during the sewage treatment process. This allowed the water temperature to remain stable, as well as the starting heat in the treatment system and the heat released, because of the oxidation of organic matter to be used to maintain the temperature during the treatment process.

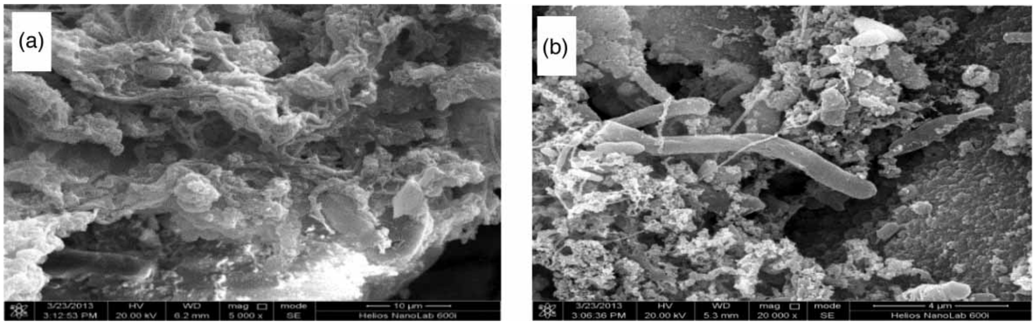

Figure 6 | Scanning electron microscopy images of the lava filtration material from (a) the secondary anaerobic biofilter (20,000× magnification) and (b) the third stage aerobic biofilter (5,000 × magnification).

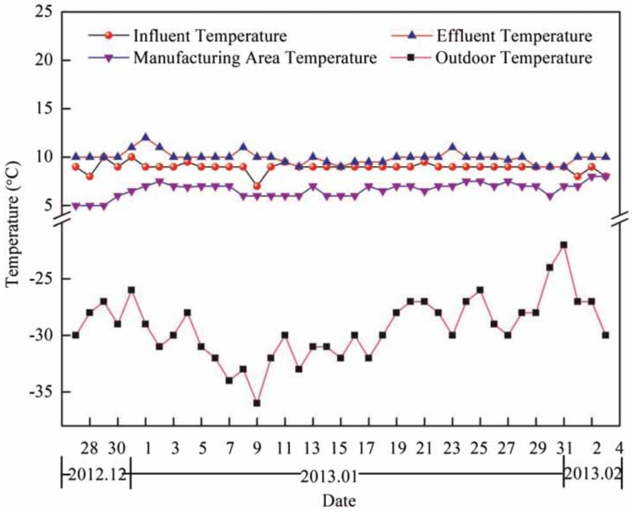

Figure 7 | Water temperatures during the sewage treatment process. As January is the coldest month at the sewage treatment plant location, it was chosen as the time to test the performance of the sewage treatment process under extremely cold conditions.

CONCLUSIONS

Full-scale tests of the enhanced physicochemical-biological wastewater treatment process showed that the system worked well in cold conditions. The average COD, TP, NH_4^+–N, and SS removal efficiencies were 89.8%, 92.9%, 94.3%, and 95.8%, respectively, using a PAC dosage of 50 mg L^{-1}. The biological phosphorus removal rate was poorer than expected, being only 27.5%, and the process required a coagulant to chemically enhance the phosphorus removal rate. Micro-membrane filtration enhanced the physicochemical removal of the pollutants, removing reasonably high amounts of organic matter, TP, and SS during preliminary treatment with coagulant added. Micro-membrane filtration greatly increased the proportion of dissolved organic pollutants, decreased the subsequent biological treatment load, removed some of the operating difficulties, and increased the wastewater treatment efficiency in cold conditions. The soluble chemical oxygen demand (SCOD)/COD removal efficiency was increased to 86% and the SS concentration was decreased to 80 mg L^{-1} when an influent with an average SS concentration of nearly 300 mg L^{-1} was treated using the micro-membrane filtration device and the PAC dosage was 50 mg L^{-1}. The back-wash cycle of the second anaerobic biofilter would be two days longer and the third aerobic biofilter process would be three days longer without adding 50 mg L^{-1} PAC to the wastewater. Biofilms grew well on the lava filtration material during the winter, and the biofilms ensured that reasonably high biological treatment efficiencies were achieved. Using the micro-membrane filtration process as the preliminary treatment and the two-stage biological aerated filter as the biological treatment, the whole process could be conducted in a compact single structure, meaning that relatively little land is needed for sewage treatment. This also means that a constant water temperature can be maintained. The process is an effective sewage treatment method for use in cold regions.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support from the Key Program of the National Natural Science Foundation of China (51038003), the National High Technology Research and Development Program of China (2012AA063508, 2011AA060906), and the Topic-Oriented Class of the State Key Laboratory of Urban Water Resource and Environment (2010DX13).

REFERENCES

Adin, A. & Asano, T. 1998 The role of physical-chemical treatment in wastewater reclamation and reuse. *Water Science and Technology* **37** (10), 70–90.

Aguilar, M. I., Sáez, J., Lloréns, M., Soler, A. & Ortuòo, J. F. 2002 Nutrient removal and sludge production in the coagulation–flocculation process. *Water Research* **36**, 2910–2919.

Amirtharajah, A. & O'Melia, C. R. 1991 Coagulation Processes: Destabilization, Mixing, and Flocculation. In: *Water Quality and Treatment*, 4th edn (F. W. Pontius, tech. ed.). AWWA, McGraw-Hill, New York, pp. 127–269.

Ben, Y., Chen, Z. L. & Xu, Z. Z. 2009 Application of immobilized psychrotrophs in ICCBR to treat domestic sewage and its microbiological investigation. *Chinese Science Bulletin* **9**, 1599–1606.

Bicudo, J. R., Westerman, P. W. & Oleszkiewicz, J. A. 2000 Proceedings of the Water Environment Federation. *Animal Residuals Management* **36**, 495–530.

Chevalier, P., Proulx, D., Lessard, P., Vincent, W. F. & de la Noüe, J. 2003 Nitrogen and phosphorus removal by high latitude mat-forming cyano-bacteria for potential use in tertiary sewage treatment. *Journal of Applied Phycology* **12** (2), 105–113.

Clark, T. & Stephenson, T. 1999 Development of a jar testing protocol for chemical phosphorus removal in activated sludge using statistical experimental design. *Water Research* **33**, 1730–1734.

Ebeling, J. M., Sibrell, P. L., Ogden, S. R. & Summerfelt, S. T. 2003 Evaluation of chemical coagulation–flocculation aids for the removal of suspended solids and phosphorus from intensive recirculating aquaculture effluent discharge. *Aquacultural Engineering* **29**, 23–42.

Farabegoli, G., Chiavola, A. & Rolle, E. 2009 The Biological Aerated Filter (BAF) as alternative treatment for domestic sewage. Optimization of plant performance. *Journal of Hazardous Materials* **171**, 1126–1132.

Franceschi, M., Girou, A., Carro-Diaz, A. M., Maurette, M. T. & Puech-Costes, E. 2002 Optimisation of the coagulation–flocculation process of raw water by optimal design method. *Water Research* **36**, 3561–3572.

Galarneau, E. & Gehr, R. 1997 Phosphorus removal from wastewaters: experimental and theoretical support for alternative mechanisms. *Water Research* **31**, 328–338.

Head, M. A. & Oleszkiewicz, J. A. 2004 Bioaugmentation for nitrification at cold temperatures. *Water Research* **38**, 523–530.

Hsu, P. H. 1976 Comparison of iron (III) and aluminium in precipitation of phosphate from solution. *Water Research* **10**, 903–907.

Mino, T., Van Loosdrecht, M. C. M. & Heujnen, J. J. 1998 Microbiology and biochemistry of the enhanced biological phosphate removal process. *Water Research* **32**, 3193–3207.

Oehmen, A., Lemos, P., Carvalho, G., Yuan, Z., Keller, J., Blackall, L. L. & Reis, M. A. M. 2007 Advances in enhanced biological phosphorus removal: from micro to macro scale. *Water Research* **41**, 2271–2300.

Pogue, A. J. & Gilbridge, K. A. 2007 Impact of protozoan grazing on nitrification and the ammonia- and nitrite-oxidizing bacterial communities in activated sludge. *Can. J. Microbiol.* **53**, 559–571.

Sathananthan, A. H. & Nottola, S. A. 2007 Digital imaging of stem cells by electron microscopy. *Stem Cell Assays* **407**, 21–41.

State Environmental Protection Administration of China 2002a *Discharge Standards of Pollutants for Municipal Wastewater Treatment Plant (GB 18918-2002)*. PR China Ministry of Rural and Urban Construction, PR China.

State Environmental Protection Administration of China 2002b *PR China Monitoring and Analytical Method on Water and Waste Water*, 4th edn. China Environmental Science Press.

Thomas, P. R., Allen, D. & McGregor, D. L. 1996 Evaluation of combined chemical and biological nutrient removal. *Water Science and Technology* **34** (1/2), 285–292.

Tsang, Y. F., Hua, F. L., Chua, H., Sin, S. N. & Wang, Y. J. 2007 Optimization of biological treatment of paper mill effluent in a sequencing batch reactor. *Biochemical Engineering Journal* **34**, 193–199.

Verstraete, W. & Philips, S. 1998 Nitrification-denitrification processes and technologies in new contexts. *Environmental Pollution.* S1 **10** (2), 717–726.

Wang, Y. N. 2007 The study on treatment of low-temperature sewage in biological aerated filter [D]. Master's thesis, Harbin Institute of Technology, pp. 44–45.

Wang, Y. Q., Han, T. W., Xu, Z., Bao, G. Q. & Zhu, T. 2005 Optimization of phosphorus removal from secondary effluent using simplex method in Tianjin, China. *Journal of Hazardous Materials* **B121**, 183–186.

Yan, M. Q., Wang, D. S., You, S. J., Qu, J. H. & Tang, H. X. 2006 Enhanced coagulation in a typical North-China water treatment plant. *Water Research* **40**, 3621–3627.

Zhang, H. L., Fang, W., Wang, Y. P., Sheng, G. P., Zeng, R. J., Li, W. W. & Yu, H. Q. 2013 Phosphorus removal in an enhanced biological phosphorus removal process: roles of extracellular polymeric substances. *Environmental Science & Technology* **47**, 11482–11489.

First received 8 December 2013; accepted in revised form 18 August 2014. Available online 9 September 2014