Comprehensive assessment of system performance in a full-scale wastewater treatment plant with an anaerobic/anoxic/aerobic membrane bioreactor combined with the ozonation process

Dan Wang, Yihui Wu, Fang Guo, Zhiping Li and Guangxue Wu

ABSTRACT

The system performance, economic cost and environmental impact of a full-scale anaerobic/anoxic/aerobic/membrane bioreactor (3AMBR) combined with the ozonation process were evaluated. The 3AMBR/ozonation process removed biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, NH_4-N and total phosphorus efficiently, with removal percentages above 94%, while the total nitrogen removal percentage was only 70%. The multiple linear regression analysis showed that hydraulic retention time (HRT) had a significant effect on nitrogen removal. A low HRT benefited nitrogen removal. Ferrous sulfate dosage close to the optimal value and a high mixed liquid suspended solid could enhance the phosphorus removal. The electricity cost accounted for 88% of the total economic costs. Greenhouse gas (GHG) emissions from the BOD oxidation and endogenous decay accounted for more than 50% of total emissions. The second largest GHG emission source was electricity consumption, accounting for 41%. The key to reduce the eutrophication was to enhance nitrogen removal. The composite cost of the 3AMBR/ozonation process was 251 CNY/t CODeq removed, among which economic cost accounted for 82.5%, while environmental impact cost accounted for a small proportion.

Key words | 3AMBR/ozonation process, economic cost, eutrophication, GHG emission, technical performance

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INTRODUCTION

The membrane bioreactor (MBR) has been widely used in wastewater treatment plants (WWTPs) because of its good effluent quality, small footprint and low sludge yield (Hospido *et al.* 2012). The number of large scale MBRs in China had reached 130 by the end of 2014, with the capacity of more than 4.5×10^6 m^3/d (Xiao *et al.* 2014). The three typical types of MBR applications are oxic-MBR, anoxic-oxic-MBR and anaerobic-anoxic-oxic-MBR (Xiao *et al.* 2014).

The basic function of a WWTP is to remove the pollutants from wastewater and to achieve the discharge standard. A technical performance evaluation can not only help to clarify the removal efficiency and effluent distribution of different pollutants, but also aid identification of the main factors affecting the removal of key pollutants. Multiple linear regression has been widely used to identify the independent variables that influence dependent variables, exploring the influence factors that affect the dependent variables (Hijosa-Valsero *et al.* 2011). However, the influence factors on nitrogen and phosphorus removal have been less investigated by multiple linear regression method.

High energy consumption has been the main reason that limits the widespread application of MBR technology in WWTPs. The energy consumption of a WWTP based on conventional activated sludge (CAS) process is 0.3–0.4 kWh/m^3, while energy consumption of MBR process is about 0.4–1 kWh/m^3 (Høibye *et al.* 2008), of which the membrane accounts for the largest proportion of total energy consumption of a WWTP, accounting for about 45% of the total energy consumption of a WWTP (Xiao *et al.* 2014). Thus, economic cost cannot be ignored when the comprehensive evaluation of the membrane technology is carried out.

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The environmental impact of the MBR process has also been paid more attention. Comparing the environmental impact of CAS and CAS + MBR processes, Ortiz *et al.* (2007) indicated CAS with MBR had more serious impact on the environment although a better effluent quality could be achieved. The technical performance, economic cost and environmental effect of five tertiary treatment processes were examined by Høibye *et al.* (2008), demonstrating that MBR process had greater impact on the environment.

The technical performance, economic cost and environmental impact of a full-scale anaerobic/anoxic/aerobic membrane bioreactor (3AMBR) combined with the ozonation process were evaluated to improve the operating performance of this WWTP. The multiple linear regression was applied to clarify the factors affecting the removal of nitrogen and phosphorus, so as to provide guidance for stakeholders and decision makers of the WWTPs.

MATERIALS AND METHODS

Wastewater treatment plant

The footprint of 3AMBR/ozonation process is 2.6 hm^2, with the service area and service population of 12.48 km^2 and 288,000. The effluent standard was Class 1A level of pollutant discharge standard of municipal WWTPs (GB18918-2002) (MOEP 2002), with the effluent standard for chemical oxygen demand (COD), biochemical oxygen demand (BOD), suspended solids (SS), total nitrogen (TN), total phosphorus (TP) and NH_4-N of 50, 10, 10, 15, 0.5 and 5 mg/L, respectively. The flowchart of the 3AMBR/ozonation process is shown in Figure 1, and the designed parameters are listed in Table 1. The chemical addition position was located after the superfine grid and before the anaerobic tank. The chemical was ferrous sulfate ($FeSO_4$), which was used for TP removal.

Evaluation methods

Technical performance evaluation

The monitored pollutants included the influent and effluent BOD, COD, SS, TN, TP and NH_4-N. Based on 355 days' monitored data, the influent and effluent concentration, removal percentage, and effluent distribution of different indicators were used to evaluate the technical performance of 3AMBR/ozonation process. The technology performance statistic (TPS) was also adopted to evaluate the wastewater treatment technology or process performance by percentage statistic of each effluent pollutant. TPS mainly comprised three levels, namely TPS-3.84%, TPS-50% and TPS-95%. TPS-3.84%, TPS-50% and TPS-95% represent the ideal, median, and reliably achievable performance of wastewater treatment, respectively (Bott *et al.* 2012).

Nitrogen and phosphorus are the main controlled pollutants, and approximately 90% of WWTPs have problems with nitrogen and phosphorus removal, especially for nitrogen removal (Zhang *et al.* 2016). In order to clarify the key factors affecting the TN and TP removal and optimize the operation of 3AMBR/ozonation, the multiple linear regression method was used, which was realized by the statistical software SPSS (Statistical Package for the Social Science). The independent variables of multiple linear regression were temperature (T), influent pH, dissolved oxygen (DO) concentration in switchable tank, influent ratio of COD and TN (COD/TN), influent ratio of COD and TP (COD/TP), sludge retention time (SRT), hydraulic retention time (HRT), sludge loading (food-to-microorganisms ratio (F/M)), mixed liquid suspended solid (MLSS), specific flux (SF) and mole ratio of Fe and the removed TP (Fe_{mol}). The dependent variables were volume loading of TN (TN_{vl}) and TP (TP_{vl}), representing the removal effect for TN and TP.

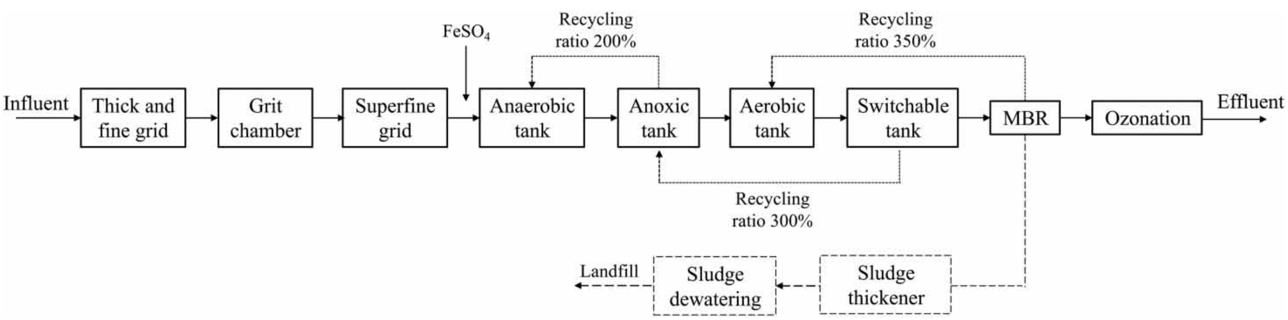

Figure 1 | The flowchart of 3AMBR/ozonation process. Note: switchable tank means the tank can be switched between anoxic and aerobic condition, so as to increase the flexibility of process adjustment for denitrification. The switchable tank in this study was actually an anoxic tank because of no aeration.

Table 1 | The designed parameters of 3AMBR/ozonation process

Parameter	Unit	Value
Capacity	10^4 m^3/d	6
Temperature	°C	15
MLSS in membrane tank	mg/L	6,000–10,000
F/M in aerobic tank	kg BOD_5/(kg MLSS·d)	0.034
Sludge retention time	d	25
Hydraulic retention time	h	17.14
Total area of MBR	m^2	63,000
Water production/relaxation period	min	7/1

Economic cost evaluation

The economic cost of a WWTP generally comprises investment cost, maintenance cost and operation cost. The operation cost refers to electricity consumption, chemical consumption and sludge treatment and disposal related cost (Verrecht *et al.* 2010). The investment expenditure was related to the construction period of a WWTP, while operation costs were the expenses during the operation phase. The economic cost related to the operation period was mainly considered in this study. So only the operation cost during operation phase was considered. The personnel cost was not taken into account because of the lack of relevant data. The operation costs of 3AMBR/ozonation process mainly included electricity, tap water and chemical consumption for phosphorus removal, sludge dewatering and membrane cleaning. The functional unit of economic cost is CNY/t COD equivalent (CODeq) removed.

Environmental effect evaluation

The two most important environmental indicators considered in this study were greenhouse gas (GHG) and eutrophication. The GHG mainly refers to CO_2, N_2O and CH_4, with the global warming potential of 1, 296 and 23, respectively (IPCC 2006). The modified Bridle model was used to calculate the GHG emission. The detailed calculation formulas are listed in Table 2. The sources of GHG emissions from WWTPs usually include on-site emissions and off-site emissions. The on-site emissions mainly refer to GHG generated from the biological treatment system of the WWTP, while off-site emissions refer to GHG generated from electricity and chemical consumption, sludge transport, etc.

The eutrophication indicator of a WWTP is divided into two categories: direct and indirect emission. The direct emission denotes the eutrophication caused by effluent discharging directly. The indirect emission refers to eutrophication caused by electricity consumption, chemical consumption, sludge disposal and so on. Because direct emission was the main reason for eutrophication of a WWTP (Hospido *et al.* 2012), direct emission of eutrophication was considered but indirect emission was neglected in this study. Different pollutants were converted into PO_4-P equivalent according to eutrophication potential when eutrophication was evaluated, with the eutrophication potential of TP, NH_4-N, NO_3-N and COD of 3.06, 0.33, 0.1 and 0.022, respectively (Guinée *et al.* 2002).

Comprehensive evaluation

The pollutant discharge fee was used to normalize different pollutants, which were unified into the CODeq. The weighting factors of COD, SS, TN and TP were 1, 2, 20 and 100, respectively (Copp *et al.* 2002). The functional units of economic cost, GHG and eutrophication were unified into 1 t CODeq removed.

Combined with the 'green tax' method (Wu *et al.* 2005), environmental impact from GHG and eutrophication were converted into environmental costs. The sum of environmental and economic costs was the comprehensive cost. According to Wu *et al.* (2005), the green tax of eutrophication and GHG were 0.58 (CNY/kg NO_3-Neq) and 0.22 (CNY/kg Ceq), respectively. After unit conversion, the green tax of eutrophication and GHG were 5.8 (CNY/kg PO_4-Peq) and 0.06 (CNY/kg CO_2eq). The composite cost consists of the sum of economic cost and environmental impact cost of removing 1 t CODeq.

RESULTS AND DISCUSSION

Technical performance

The effluent distribution of different pollutants is shown in Figure 2. The concentrations in influent and effluent, removal efficiency and TPS are listed in Table 3. The effluent distribution based on 355 days' performance data indicated that the concentration range of BOD, COD, TN and TP were 0.5–2, 8–13, 5–13 and 0.1–0.25 mg/L, respectively. The effluent concentration of SS and NH_4-N were mainly less than 4 mg/L and 1 mg/L. The reliably achievable performance (TPS-95%) of different pollutants in the 3AMBR/ozonation process was better than the discharge standard of Class 1A level, with the discharge standard of BOD, COD, SS, TN, TP and NH_4-N of 10, 50, 10, 15, 0.5 and 5 mg/L, respectively (MOEP 2002). The average effluent concentration of BOD,

Table 2 | The modified Bridle model for GHG emissions calculation

Categories for GHG emissions	Formula	Reference for formula and coefficient
CO_2 generated from BOD oxidation	$CO_{2,BODox} = 1.1 \times (BOD_{ox}/f - 1.42 \times X_{net,produced})$ $X_{net,produced} = Y/(1 + k_D \times SRT) \times BOD_{ox}$ $CO_{2,BODox}$: CO_2 generated from BOD oxidation, kg CO_2/d BOD_{ox}: BOD oxidation, kg/d f: BOD_5/BOD_u, 0.68 $X_{net,produced}$: net biomass, kg VSS/d Y: sludge yield, 0.68 kg VSS/kg $BOD_{removed}$ k_D: endogenous respiration coefficient, 0.05, 1/day SRT: sludge retention time, d	Snip (2010) f, k_D: Monteith et al. (2005)
CO_2 generated from endogenous respiration	$CO_{2,decay} = 1.947 \times Q_{in} \times HRT \times MLVSS \times k_D$ $CO_{2,decay}$: CO_2 generated from endogenous respiration, kg CO_2/d Q_{in}: influent capacity, 10^4 m^3/d HRT: hydraulic retention time, h MLVSS: mixed liquor volatile suspended solids, mg/L k_D: endogenous respiration coefficient, 0.05, 1/day	Snip (2010)
CO_2 utilized by nitrification	$CO_{2,credit} = 0.308 \times [Q_{in} \times (TN_{in} - TN_{eff}) - X_{net,produced} \times 14/113]$ $CO_{2,credit}$: CO_2 utilized by nitrification, kg CO_2/d TN_{in}: influent TN concentration, kg N/m^3 TN_{eff}: effluent TN concentration, kg N/m^3 0.308: CO_2 consumed by nitration of 1 kg N	Snip (2010)
CO_2 generated from electricity	$CO_{2,\ electricity} = f_{electricity} \times C_{electricity}$ $CO_{2,\ electricity}$: CO_2 generated by electricity, kg/d $f_{electricity}$: electricity emission factor, 0.66 kg CO_2eq /kWh $C_{electricity}$: electricity consumption, kWh/d	Snip (2010) $f_{electricity}$: Song et al. (2013)
N_2O emitted from nitrogen removal	$N_2O = Q_{in} \times TN_{in} \times R_{N2O,generation}$ N_2O: N_2O emitted from nitrogen removal, kg/d TN_{in}: influent TN concentration, mg/L $R_{N2O,generation}$: conversion factor, 0.004 kg N_2O/kg N feed	Snip (2010) $R_{N2O,generation}$: Snip (2010)
CH_4 generated from biological treatment process	$CH_4 = f_{CH4} \times [Q_{in} \times (COD_{in} - COD_{eff})]$ CH_4: CH_4 emission from biological treatment process, kg/d COD_{in}: influent COD concentration, kg COD/m^3 COD_{eff}: effluent COD concentration, kg COD/m^3 f_{CH4}: CH_4 emission factor, 0.0039 kg CH_4/kg COD	Cai et al. (2015) f_{CH4}: Cai et al. (2015)
CO_2 generated from sludge transport	$CO_{2,\ transport} = n \times L \times f_{fuel} \times f_{transport}$ $CO_{2,\ transport}$: CO_2 emission from sludge transport, kg CO_2eq/d n: transport time per year, time/year L: transport distance per time, km/time f_{fuel}: gasoline consumption per kilogram, 0.554 L/km $f_{transport}$: emission factor of gasoline, 2.5 kg CO_2eq/L	f_{fuel}, $f_{transport}$: de Haas et al. (2008)
CO_2 generated from chemical consumption	$CO_{2,chemical} = W_{PAC} \times f_{PAC} + W_{PAM} \times f_{PAM} + W_{NaClO} \times f_{NaClO}$ $CO_{2,chemical}$: CO_2 emission from chemical consumption, kg CO_2/d $W_{chemical}$: chemical consumption, kg chemical/d f_{PAC}: emission factor of PAC, 1.182 kg CO_2eq/kg PAC f_{PAM}: emission factor of PAM, 1.182 kg CO_2eq/kg PAM f_{NaClO}: emission factor of NaClO, 0.65 kg CO_2eq/kg NaClO	f_{PAC}, f_{PAM} : de Haas et al. (2008) f_{NaClO}: Liu et al. (2010)

PAC: polyaluminum chloride; PAM: polyacrylamide.

COD, SS, TN, TP and NH_4-N in 3340 WWTPs in China were, 33.8, 12.1, 10.9, 0.7 and 4.1 mg/L, respectively (Sun et al. 2016). The effluent concentration of different pollutants in 3AMBR/ozonation were lower than the national average value. The removal efficiency of BOD, COD, SS and NH_4-N were all above 95%. The TP removal percentage was 94%, whereas the removal efficiency of TN was only 70%.

Factors affecting the removal of TN and TP

The main parameters affecting the removal of TN and TP are shown in Table 4. The multiple linear regression results are presented in Table 5. Nitrogen removal of the 3AMBR/ozonation process was significantly affected by HRT and temperature. The greater absolute value of the standardized

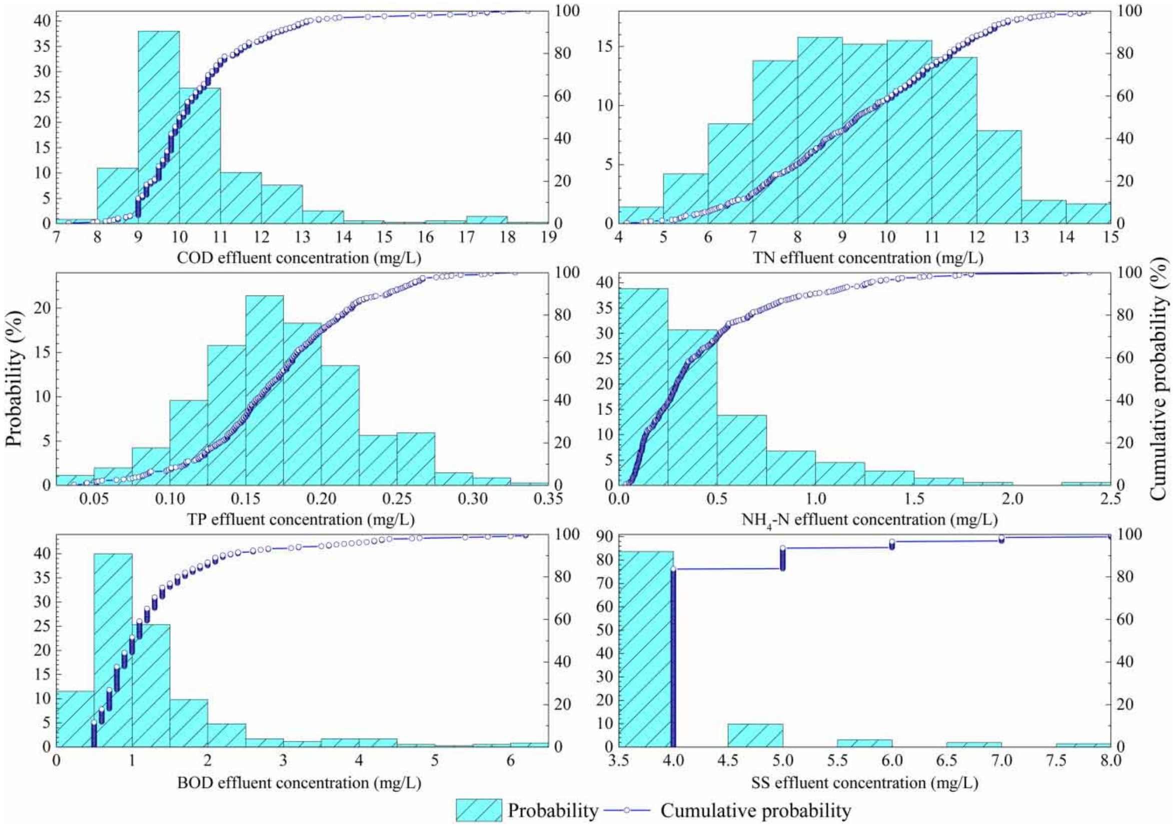

Figure 2 | Distribution of effluent pollutant concentration of the 3AMBR/ozonation process.

Table 3 | Technical performance of the 3AMBR/ozonation process

	N	Influent mg/L	Effluent mg/L	Removal efficiency %	TPS-3.84% mg/L	TPS-50% mg/L	TPS-95% mg/L
BOD	355	125.8 ± 84.2	1.3 ± 1	98.7 ± 1.2	0.5	1.0	3.6
COD	355	278.2 ± 170.3	10.5 ± 1.6	95.2 ± 2.4	9.0	10.1	13.1
SS	355	215.2 ± 167.5	4.3 ± 0.7	97.4 ± 1.2	4	4	6
TN	355	32.9 ± 9	9.4 ± 2.2	69.9 ± 8.9	5.7	9.3	12.7
TP	355	3.3 ± 1.4	0.2 ± 0.1	93.9 ± 2.7	0.08	0.17	0.26
NH_4-N	355	24 ± 6.9	0.4 ± 0.4	98.2 ± 1.6	0.07	0.31	1.27

coefficient of independent variables denote the greater influence on dependent variables (Chatterjee & Hadi 2012). The effect of HRT on nitrogen removal was greater than that of temperature (Table 5). HRT had negative effect on nitrogen removal, due to the low influent COD/TN, with the average influent COD/TN value of 7.87. Under the condition of insufficient influent carbon source, the long HRT will not meet the denitrification requirement for carbon sources. If the influent COD/TN of WWTPs is between 8 and 12, good or complete denitrification will be achieved (Henze & Harremoes 2002). Microbial activity may be sensitive to temperature fluctuation, and slight temperature change may affect nitrogen removal efficiency. The R^2 of the TN multiple linear regression equation is less than 0.5. Although the multiple linear regression equation cannot predict the TN removal exactly when R^2 is less than 0.5, the independent variables of HRT and temperature in the regression equation had significant effect on TN removal. The TN volume loading can be improved by controlling the independent variables of HRT and temperature. The exact functional relationship between the independent variable and the dependent variable for TN

Table 4 | Influence factors on TN and TP removal of 3AMBR/ozonation process

Parameter	Unit	N	Minimum	Maximum	Average	Standard deviation
DO in switchable tank	mg/L	40	0.12	1.85	0.70	0.43
pH	–	40	7.26	7.96	7.49	0.14
T	°C	40	12.00	24.00	18.13	3.42
MLSS	mg/L	40	5,834.17	8,607.00	7,518.04	610.84
SF	$L/(m^2 \cdot h \cdot kPa)$	40	1.16	3.21	2.04	0.57
F/M	kg BOD_5/(kg MLSS·d)	40	0.01	0.05	0.03	0.01
SRT	d	40	12.63	48.69	32.95	8.34
HRT	h	40	14.66	22.94	17.46	2.64
COD/TN	–	40	3.83	14.66	7.87	2.79
COD/TP	–	40	41	320	95	51
Fe_{mol}	Fe mol/P mol	40	0.34	1.70	0.88	0.30
TN volume loading	$g/(m^3 \cdot d)$	40	10.34	57.72	29.91	9.27
TP volume loading	$g/(m^3 \cdot d)$	40	1.63	6.94	3.61	1.12

Table 5 | The multiple linear regression of TN and TP volume loading in the 3AMBR/ozonation process

Regression equation	Standardized coefficient	R^2	Independent variables
$TN_{vl} = 77.994 - 1.844HRT - 0.876T$	HRT = −0.524, T = −0.323	0.264	DO, pH, T, MLSS, SF, F/M, SRT, HRT, COD/TN, Fe_{mol}
$TP_{vl} = 2.132 - 3.107Fe_{mol} + 0.001MLSS$	Fe_{mol} = −0.84, MLSS = 0.306	0.698	DO, pH, T, MLSS, SF, F/M, SRT, HRT, COD/TP, Fe_{mol}

removal can be determined by other mathematical statistical methods.

The dosage of $FeSO_4$ (Fe_{mol}) and MLSS in the membrane tank had significant effect on TP removal. Comparing the absolute value of standardized coefficient, the dosage of $FeSO_4$ had greater effect on TP removal than did MLSS. The smaller the molar addition of iron, the better the phosphorus removal effect. Taking the $FeCl_3$ as flocculant, Smith *et al.* (2008) explored the main influencing factors on TP removal. Smith *et al.* (2008) demonstrated that an optimal $FeCl_3$ existed. The TP removal efficiency decreased if the $FeCl_3$ dosage exceed the optimal value. Fe atoms were more likely to interact with other Fe atoms than to interact with P if $FeCl_3$ addition was more than the optimal value, resulting in the decreased TP removal efficiency. Similarly, the dosage of $FeSO_4$ in 3AMBR/ozonation may exceed the optimal dosage for TP removal, which leads to the reduction of TP removal efficiency. The multiple regression equation can confirm the influence factors affecting TP removal and judge the favorable tendency of the independent variable, but the optimal $FeSO_4$ dosage cannot be determined. The optimal $FeSO_4$ dosage should be determined by laboratory test. The designed MLSS in the membrane tank was 8000–10,000 mg/L, while the measured MLSS was 7,518 mg/L. Thus, the high MLSS could be beneficial to increase microbial biomass for phosphorus removal, so as to improve phosphorus removal efficiency. The multiple regression equation of TP indicated that an acceptable linear relationship existed between the independent variables and dependent variables, because the R^2 of the TP regression equation was greater than 0.5. The measured and calculated TP volume loadings are shown in Figure 3. The calculated TP volume loading was obtained by the regression equation.

Economic cost evaluation

The consumption and economic cost of electricity, tap water and chemicals of 3AMBR/ozonation are listed in Table 6. Tap water was used in the daily life of employees in the WWTP. The chemicals $FeSO_4$ and polyacrylamide (PAM) (flocculant) were used for TP removal and sludge dewatering, respectively. The chemical used for MBR cleaning was polyaluminum chloride (PAC), sodium hydroxide (NaOH), sodium hypochlorite (NaClO) and citric acid, among which NaClO and PAC accounted for 43% and 54%, respectively. Electricity contributed the most to the economic cost, with the proportion of 88%. The energy distribution analysis of this WWTP in 2013 showed that the MBR tank consumed the most energy (43.0%), followed

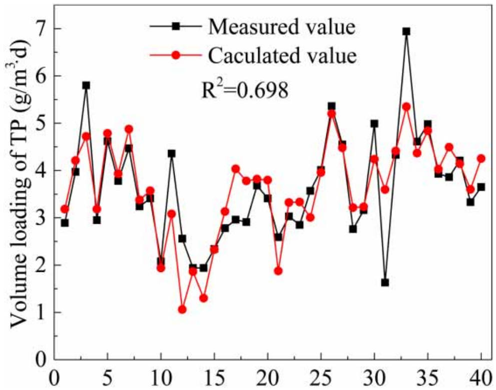

Figure 3 | Comparison of measured and calculated TP volume loading of the full-scale 3AMBR/ozonation process.

by the anaerobic/anoxic/oxic (A/A/O) tank (37.3%). Xiao *et al.* (2014) investigated the energy consumption of several large scale MBR WWTPs in China, indicating that the MBR tank accounted for more than 40% of total energy consumption and the aerobic tank accounted for about 30%. Therefore, the key to reduce the economic cost of 3AMBR/ozonation is to ensure the effluent meets the discharge standard, and at the same time, to control the aeration of the MBR and aerobic tanks appropriately.

Environmental impact

The GHG is subdivided into the CO_2 generated from electricity and chemical consumption sludge transport and CO_2, CH_4 and N_2O generated from biological treatment in this study. The impacts of NaOH and citric acid on GHG were neglected in this study, because the consumption of NaOH and citric acid were less than 3.5% of total chemical consumption for membrane cleaning. The GHG emission of this WWTP is presented in Figure 4.

The BOD oxidation and endogenous respiration generated the most GHG, accounting for more than 50% of total GHG, with the GHG emission of 217 kg CO_2/t CODeq removed. Electricity generated the second largest GHG emission, accounting for 41% of total GHG (177 kg CO_2/t CODeq removed). Chemical consumption and sludge transport contributed the least to GHG, accounting for 0.9% and less than 0.07%, respectively. Therefore, biological treatment and electricity were the main sources of GHG emission. Hospido *et al.* (2012) used life cycle assessment to evaluate the GHG emission of four different MBR processes without considering the contribution of biological metabolic processes, and the final results showed that electricity contributed most to GHG.

Table 6 | The economic evaluation of the 3AMBR/ozonation process

	Consumption		Economic cost	
	Consumption	unit	Cost	unit
Electricity	280	kWh/t CODeq removed	182	CNY/t CODeq removed
Tap water	0.06	m^3/t CODeq removed	0.29	CNY/t CODeq removed
$FeSO_4$	11	kg/t CODeq removed	4	CNY/t CODeq removed
PAM	0.24	kg/t CODeq removed	9	CNY/t CODeq removed
PAC	4	kg/t CODeq removed	3	CNY/t CODeq removed
NaOH	0.06	kg/t CODeq removed	0.25	CNY/t CODeq removed
NaClO	5	kg/t CODeq removed	6	CNY/t CODeq removed
Citric acid	0.29	kg/t CODeq removed	3	CNY/t CODeq removed

The effluent NO_3-N contributed the most eutrophication, accounting for 80% of total eutrophication emission, followed by effluent TP (12.3%), while effluent COD and NH_4-N contributed the least, accounting for less than 5% (Figure 5). Therefore, the main causes of eutrophication were effluent nitrogen and phosphorus. Gallego *et al.* (2008) and Garrido-Baserba *et al.* (2014) studied the eutrophication indicator of effluent from different WWTPs, and the results also demonstrated that nitrogen and phosphorus were the main causes of eutrophication. According to the technical performance evaluation, the removal efficiency of TP in the 3AMBR/ozonation process reached 94%, and

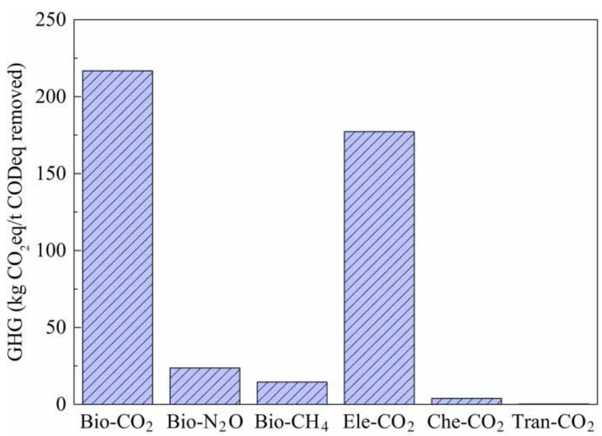

Figure 4 | GHG emission of the 3AMBR/ozonation process. Bio: emission from biological treatment (A/A/O) process; Ele: emission form electricity generation; Che: emission from chemical consumption; Tran: emission from sludge transport.

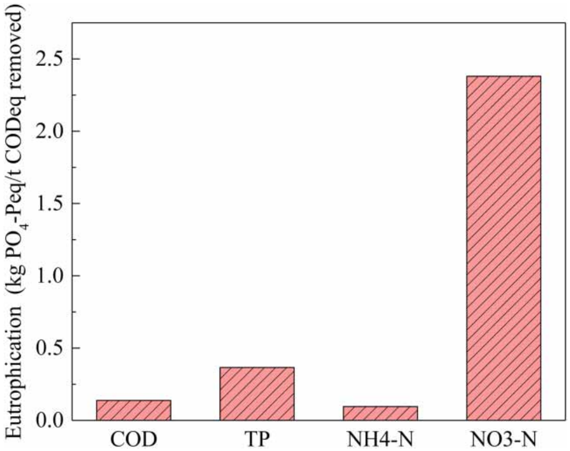

Figure 5 | Eutrophication of the 3AMBR/ozonation process.

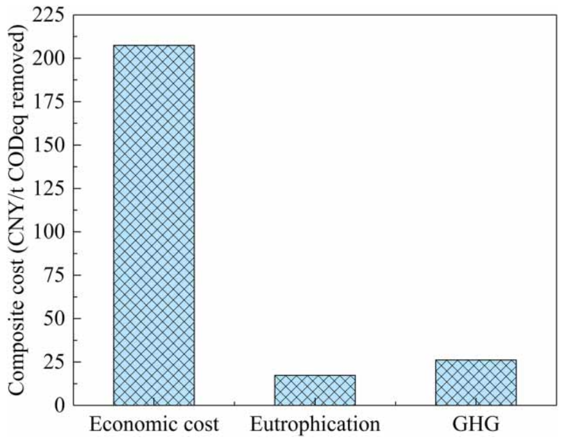

Figure 6 | Composite cost of the 3AMBR/ozonation process.

the reliably achievable effluent TP concentration (TPS-95%) was 0.328 mg/L, which was less than the national average value of 0.5 mg/L (Sun *et al.* 2016). Therefore, there was no adequate room for the improvement of TP effluent concentration. On the contrary, the alleviation of effluent eutrophication mainly depends on increasing the removal efficiency of TN. Compared with other pollutants, the TN removal efficiency was the lowest, only 70%. For the average concentration of effluent TN, there was no significant different between 3AMBR/ozonation (9.4 mg/L) and other WWTPs in China (10.9 mg/L) (Sun *et al.* 2016). The 3AMBR/ozonation process has certain potential for further removal of TN. Therefore, the improvement in TN removal efficiency of the 3AMBR/ozonation process will help to reduce the effluent eutrophication.

Comprehensive evaluation

The comprehensive evaluation result is presented in Figure 6. The composite cost represents the comprehensive evaluation index in this study. The composite cost comprises three parts, namely economic cost, eutrophication cost and GHG cost. The economic cost was the highest, accounting for 82.5% of the composite cost, with the value of 208 CNY/t CODeq removed. Environmental cost accounted for a small proportion, among which GHG cost was 27 CNY/t CODeq removed (10.6%) and eutrophication cost was 16 CNY/t CODeq removed (7%). Because electricity contributed the most to the economic cost, it was the key to reduce the composite cost of the 3AMBR/ozonation process by saving energy.

Some pilot tests on energy saving of the 3AMBR/ozonation process were carried out. Through the pilot test of this WWTP, Huang *et al.* (2017) found that the effluent quality would still meet the discharge standard if DO concentration in aerobic tank were controlled at less than 0.3 mg/L. Li *et al.* (2016) indicated it helped to save energy if the recycling ratio from MBR to aerobic tank was increased and aeration in the aerobic tank was controlled. When the recycling ratio from the membrane tank to the aerobic tank was increased from 3.5Q to 6.8Q (Q: influent flow), the blast aeration in the aerobic tank can be neglected and the effluent quality was much better (Li *et al.* 2016).

CONCLUSIONS

The 3AMBR/ozonation process removed BOD, COD, SS, NH_4-N and TP efficiently, with removal percentages all above 94%. The removal percentage of TN was only 70%. The low HRT would be beneficial to nitrogen removal. $FeSO_4$ dosage was close to the optimal value and relatively high MLSS could enhance the phosphorus removal. Electricity consumption was the main contributor to economic cost, accounting for 88% of the total economic costs. Biological treatment system and electricity consumption were the main sources of GHG emissions. The key to reduce the eutrophication was to improve the denitrification efficiency. The comprehensive cost of the 3AMBR/ozonation process was 251 CNY/t CODeq removed, of which economic cost accounted for 82.5%, while environmental impact cost accounted for only a small proportion.

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