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Comprehensive Evaluation of Socio-economic and Environmental Impacts using Membrane Bioreactors for Sewage Treatment in Beijing

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Membrane bioreactors (MBRs) technology has a higher efficiency of water pollutants reduction than conventional sewage treatment technologies. However, the application of MBRs technology on sewage treatment is limited due to its high operating cost and investment. In this study, a comprehensive linear simulation model was constructed to evaluate the socio-economic impact and environmental sustainable development of sewage treatment by using MBRs technology. Moreover, we select Beijing to make an empirical study. The simulation result forecasts that using MBRs technology, T-P, T-N and COD in 2020 can be reduced by 22%, 15% and 66%, respectively, compared with 2010, and the goal of reduction of both energy consumption intensity and GHG emission intensity is achievable. Therefore, sewage treatment by MBRs technology is feasible in the view of socio-economic sustainable development.

Key words: Membrane bioreactors, Comprehensive evaluation, Model, Sewage, Beijing.

Water pollution control has been a matter of public concern for more than a century[1]. Advanced technologies for sewage treatment are often advocated in order to decrease the impact of water environmental pollution. Membrane bioreactors (MBRs) are now widely used for municipal and industrial wastewater treatment because of its compact plant footprint and high-quality effluent[2-10]. However, several disadvantages, such as the high operation cost, high energy consumption and membrane fouling, limit its future utilization[11-13]. It is necessary to apply a comprehensive evaluation of environmental and economic impact for MBRs, whereas few studies have been conducted to comprehensively evaluate with respect to environment and socio-economy. In the view of research content, previous studies on the MBRs technology are roughly divided into four portions: (1) membrane fouling, (2) effluent quality, (3) energy consumption and (4) cost considerations[13]. The former two studies mainly focus on optimal method to release the membrane fouling (e.g. [,4 13, 15-16]) and the efficiency of water pollutants reduction (e.g. [17-20]), respectively, while the latter two intend on the assessment of energy consumption and the operation/maintenance of the MBRs technology (e.g. [3, 4, 13, 21-26]). By contrast, the comprehensive evaluation of environmental and

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socio-economic impacts was rarely investigated. The researches of MBRs technology assessment can be divided into two categories by the varied methods, i.e. comparison method and life cycle analysis (LCA). For comparison method, the investment scale and the costs, including running cost, maintenance cost and power consumption, are analyzed to find out the cheapest option from different mixed procedures of MBRs[7, 13, 21-26]. The weakness of this kind of researches lies on the less consideration of the technology on the environment or socio-economy. Comparatively, the studies of LCA assessed MBRs from environmental and cost aspects rather than the impacts on socio-economy[3, 27].

The integrated approach has been used in modeling since the late 1960s when the input-output model has been already applied in environmental and natural resource field. In many integrated economic and environmental models, natural resource inputs and pollutants are expressed in terms of physical units, while economic exchanges are expressed in terms of monetary units[28]. The optimization and comprehensive evaluation model based on material balance, energy balance and economic balance is suitable for evaluating water treatment technologies[29]. Many studies using this approach have been done to assess wastewater treatment technologies[30-34], but the energy consumption and greenhouse gas (GHG) emission have been little taken into account in these studies.

In light of the above discussion, the purposes of this paper are as follows:

(i) Establish a dynamic comprehensive optimization simulation model which considers water pollutant emission, energy consumption, GHG emission and gross regional product (GRP) growth;

(ii) Evaluate the water pollutants reduction, energy consumption intensity, GHG emission intensity and rate of GRP growth impacts of MBRs technology in sewage treatment.

(iii) Suggest an optimal policy can achieve the goal of environmentally sustainable economic development.

Model

This study constructed a comprehensive optimization simulation model based on an input output table, material and energy balance to simulate socio-economic and environmental development. The simulation duration is from 2011 to 2020. Simulation for this comprehensive model is performed by Lingo software. By comparing the simulation results for different scenarios, the environmental and economic impacts of sewage treatment have been estimated with different combinations of technologies. According to the simulation results, we can provide detailed information about economic growth, water pollutant reduction, energy consumption, GHG emission, and propose optimal policy with adopting MBRs technology for sustainable development.

Model framework

The water pollutant model and economic model have been constructed in this study integrating the previous researches[30, 32-34]. This study is improved by introducing energy balance model and GHG emission model. This comprehensive model consists of one objective function (Maximize GRP) and four sub-models (a water pollutant balance model, an energy model, a GHG model and a socio-economic model) (Fig. 1). The economic model describes the relationship between economic activity and the emission of water pollutants. The water pollutant model depicts changes in the level of water pollutants generated. The pollutants measured in this study are total nitrogen (T-N), total phosphorus (T-P) and chemical oxygen demand (COD). The energy model represents the relationship between energy demand (consumption by industry, new technology and final consumption) and supply (from energy production enterprises and dispatch). The energy measured is ton of standard coal (TCE). The GHG model set up the relationship between energy consumption and GHG emission. The GHG measured in this study are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

The evaluation indicators used in this work are economy, environment and energy. These indicators are described by GRP, total load water pollutions and GHG emission intensity (GHG emission per billion GRP) and energy consumption intensity (energy consumption per billion GRP) respectively.

Simulation model formulation

In this simulation model, there are two

types of variables: endogenous (en) and exogenous (ex). The exogenous parameters are calculated based on current data; the endogenous variables will be determined by simulation.

Objective function

The maximization of the objective function places primary importance upon economic activities, which are calculated by the equilibrium solutions of the following structural equation:

$$Max\sum_{t=1}^{10}\frac{1}{(1+\rho)^{(t-1)}}GRP(t) \quad ...(1)$$

ρ: social discount rate which is a parameter used to help to choose the value of diverting funds to social projects (ex), ρ=0.05;

$GRP(t)$: Gross regional product (en);

The water pollutants model

Factors of water pollutant emission have been considered, such as population growth, GRP growth, types of land use and industry structure. It is assumed that water pollutants for economic activity flow into the rivers. There are three sources of water pollutant discharge from economic activity: household, industry, and nonpoint sources. Herein, the pollutants contained in rainfall have been examined separately as one part of total water pollutant emissions regardless of its small amount[32, 35-36]. Consequently, the pollutants emitted via rainfall were excluded from nonpoint sources. Finally, the water pollutants contained in the treated and untreated sewage flow into the rivers. The flow is assumed to flow into rivers directly, since it is difficult to collect the water pollutants added by nonpoint sources. Consideration of regional development imbalances, we divide the target area into some sub-regions.

Total water pollutant load

$$TQ^p(t)=\sum_j WP_j^p(t) \quad (p=1, \text{T-P}; p=2, \text{T-N}; p=3, \text{COD}) \quad ...(2)$$

$TQ^p(t)$: total net load of water pollutant *p* at time *t* (en);

$WP_j^p(t)$: load of water pollutant *p* in region *j* at time *t* (en);

The constraints for the total water pollutant load

$$TQ^p(t) \leq TQC^p(t) \quad ...(3)$$

$TQC^p(t)$: maximum allowable amounts of water pollutant *p* at time *t* (en);

$TQC^p(t)$: maximum allowable amounts of water pollutant *p* at time *t* (en);

Water pollutant load of sub-region

$$WP_j^p(t) = QR_j^p(t) + RQ_j^p(t) \quad ...(4)$$

$QR_j^p(t)$: load of water pollutant *p* in rivers at time *t* (en);

$RQ_j^p(t)$: load of water pollutant *p* from rainfall at time *t* (en);

Water pollutant flow through rivers

$$QR_j^p(t) = (1-\nu)\cdot SECQ_j^p(t) \quad ...(5)$$

ν : river self-purification rate (ex);

$SECQ_j^p(t)$:water pollutant *p* contributed by economic activities in the region *j* at time *t* (en);

Water pollutant contributed by economic activities

$$SECQ_j^p(t) = HQ_j^p(t) + UIQ_j^p(t) + NQ_j^p(t) - SEQ_j^p(t) \quad ...(6)$$

$HQ_j^p(t)$: water pollutant *p* emitted by households in region *j* at time *t* (en);

$UIQ_j^p(t)$: water pollutant *p* emitted by industry in region *j* at time *t* (en);

$NQ_j^p(t)$: water pollutant *p* emitted by nonpoint sources in region *j* at time *t* (en);

$SEQ_j^p(t)$: water pollutant *p* reduced by sewage plants in region *j* at time *t* (en);

Load of water pollutants from nonpoint sources

$$NQ_j^p(t) = \sum_g EL^g \cdot L_j^g(t) \quad ...(7)$$

EL^g : coefficient of water pollutant *p* emitted by land use *g* (ex);

$L_j^g(t)$: area of land use *g* in region *j* at time *t* (en);

Water pollutants emitted by households

$$HQ_j^p(t) = Z_j(t)\cdot EH^p \quad ...(8)$$

$Z_j(t)$: number of households in region *j* at time *t* (en);

EH^p : emission coefficient of water pollutant *p* per household (ex);

$$Z_j(t+1) = Z_j(t) \cdot (1+\mu) \quad ...(9)$$

μ: household growth rate (ex);

Water pollutants emitted by industry

Level of water pollutants for industry is dependent upon production. We describe relationship of production and emission of water pollutant via coefficient of water pollutants emissions of industry.

$$UIQ_j^p(t) = \sum_m x_j^m(t) \cdot EUI^m \quad ...(10)$$

$x_j^m(t)$: production of industry *m* in region *j* at time *t* (en);

EUI^m : emission coefficient of water pollutant *p* of industry *m* (ex);

Water pollutant reduced by sewage plants

Water pollutant reduced by sewage plants has two portions. One is reduced by existing sewage plants. The other is reduced by new sewage plants, which will use advanced technologies.

$$SEQ_j^p(t) = SEQ_j^a(t) + SEQ_j^b(t) \quad ...(11)$$

$SEQ_j^a(t)$: load of water pollutant *p* reduced by the existing sewage plants which use technology *a* in region *j* at time *t* (en);

$SEQ_j^b(t)$: load of water pollutant *p* reduced by the new sewage plants which use technology *b* in region *j* at time *t* (en);

$$SEQ_j^a(t) = \sum_a QSE_j^a(t) \cdot \alpha^a \quad ...(12)$$

$QSE_j^a(t)$: amount of sewage treated by existing plants which use original technology *a* in region *j* at time *t* (ex);

α^a : coefficient of reduction of pollutant *p* by sewage treatment technology *a* (ex);

$$SEQ_j^b(t) = \sum_b QSE_j^b(t) \cdot \alpha^b \quad ...(13)$$

$QSE_j^b(t)$: amount of sewage treated by new sewage plants which use technology *b*in region *j* at time *t* (en);

α^b : coefficient of reduction of pollutant *p* by sewage treatment technology *b* (ex);

Load of water pollutants from rainfall

$$RQ_j^p(t) = ER^p(t) \cdot L_j \quad ...(14)$$

L_j : emission coefficient of rainfall for pollutant *p* (ex), ER^1=47 kg/ km2-year, ER^2=1,124 kg/ km2-year, ER^3=2,091 kg/ km2-year[35-36];

: total area of region *j* (ex);

Energy model

The energy model draws the relationship between energy demand and supply. Energy is demanded by industry production, sewage treatment and final consumption. Energy is supplied by energy production enterprises and dispatch. In order to realize socio-economic development, energy supply must equal or more than energy demand.

The total energy demand

$$TED(t) = IED(t) + SWED(t) + FCED(t) \quad ...(15)$$

TED (t) : total amount of energy demand at time *t* (en);

IED (t): amount of energy demand of industry at time *t* (en);

SWED (t): amount of energy demand of sewage treatment at time *t* (en);

FCED (t): amount of energy demand of final consumption at time *t* (en);

The amount of energy demand of industry

$$IED(t) = \sum_j \sum_m x_j^m \cdot ED^m \quad ...(16)$$

ED^m : coefficient of energy demand of industry *m* (ex);

The amount of energy demand of sewage treatment

$$SWED(t) = SWED^a(t) + SWED^b(t) \quad ...(17)$$

$SWED^a$ *(t)* :total amount of energy demand by existing sewage plants which use technology *a* at time *t* (en);

$SWED^b$ *(t)*: total amount of energy demand by new sewage plants which use technology *b* at time *t* (en);

$$SWED^{a}(t)=\sum_{j}\sum_{a}QSE_{j}^{a}(t)\cdot EDC^{a} \quad ...(18)$$

EDC^{a} : coefficient of energy demand of technology *a* (ex);

$$SWED^{b}(t)=\sum_{j}\sum_{b}QSE_{j}^{b}(t)\cdot EDC^{b} \quad ...(19)$$

EDC^{b} : coefficient of energy demand of technology *b* (ex);

The amount of energy demand of final consumption

$$FCED(t)=C(t)\cdot FCC \quad ...(20)$$

C(t): final consumption at time *t* (en);
FCC : the coefficient of energy demand of final demand section (ex);
The total energy supply

$$TES(t)=EIS(t)+DSP(t) \quad ...(21)$$

TES (t): total amount of energy supply at time *t* (ex);
EIS (t): energy supply of energy industry at time *t* (ex);
DSP (t): total amount of energy dispatch at time *t* (ex);
Energy balance

$$TED(t)\leq TES(t) \quad ...(22)$$

The GHG model

The GHG model gives a description of the relationship between energy consumption and GHG emission. GHG emission is determined by energy consumption. The sources of GHG emission are industry production, sewage treatment and final consumption.

Total CHG emission

$$TGHG(t)=TG^{1}(t)+TG^{2}(t)\cdot GWP^{2}+TG^{3}(t)\cdot GWP^{3}(t) \quad ...(23)$$

$$TG^{n}(t)=TGI(t)+TGSW(t)+TGFC(t)$$

n=1, CO_2; n=2, CH_4; n=3, N_2O ...(24)
TGHG(T): total amount of GHG emission at time *t* (en);
$TG^{n}(t)$: amount of GHG *n* emission at time *t* (en);
TGI (t): amount of GHG emission of industry at time *t* (en);
TGSW (t): amount of GHG emission of sewage at time *t* (en);
TGFC (t)*)*:amount of GHG emission of final consumption (en);
GWP : potential index of greenhouse effect;
Amount of GHG emitted by industry

$$TGI(t)=\sum_{j}\sum_{m}x_{j}^{m}(t)\cdot EC^{m} \quad ...(25)$$

$EC^{(m)}$:coefficient of greenhouse gas of industry *m* (ex);

Amount of GHG emitted by sewage

GHG emission of sewage has three sources, which are original sewage plants, new sewage plants and untreated sewage.

$$TGSW(t)=TGSW^{a}(t)+TGSW^{b}(t)+TGSW^{U}(t) \quad ...(26)$$

$TGSW^{a}(t)$: amount of GHG emitted by existing sewage plants which use technology *a* at time *t* (en);
$TGSW^{b}(t)$: amount of GHG emitted by new sewage plants which use technology *b* at time *t* (en);
$TGSW^{U}$: amount of GHG emitted by untreated sewage at time *t* (en);

$$TGSW^{a}(t)=\sum_{j}\sum_{a}QSE_{j}^{a}(t)\cdot EC^{a} \quad ...(27)$$

coefficient of greenhouse gas of existing sewage plants which use sewage treatment technology *a*(ex);

$$TGSW^{b}(t)=\sum_{j}\sum_{b}QSE_{j}^{b}(t)\cdot EC^{b} \quad ...(28)$$

EC^{b} : coefficient of greenhouse gas of new sewage plants which use sewage treatment technology *b* (ex);

$$TGSW^{U}(t)=\sum_{j}QSET_{j}^{U}(t)\cdot EC^{U} \quad ...(29)$$

$QSET_{j}^{U}(t)$:amount of untreated sewage in region *j* at time *t*;
EC^{U} : coefficient of greenhouse gas of untreated sewage (ex);
Amount of GHG emitted by final consumption

$$TGFC(t)=C(t)\cdot EFC \quad ...(30)$$

C(t): final consumption at time *t* (en);
EFC : coefficient of greenhouse gas emitted by

final consumption (ex);

The economic model

The total production of each industry is determined by balances between supply and demand[32]. The production is dependent on the Leontief input-output coefficient matrix, consumption, investment and net export[35]. Variables related to the investment in advanced technologies are introduced in our work to assess the impact of new plant construction on production.

$$X^m(t) \geq A \cdot X^m(t) + C(t) + i^m(t) + \beta_m^b I^b(t) + e^t(t) \quad ...(31)$$

$$I^b(t) = \sum_j \sum_b I_j^b(t) \quad ...(32)$$

$$X^m(t) = \sum_j x_j^m(t) \quad ...(33)$$

X (t):column vector of the *mth* element is the total product of industry *m* in the target area at time *t* (en);

A: input-output coefficient matrix (ex);

C (t): total consumption at time *t* (en);

$i^m(t)$: total investment in industry *m* at time *t* (ex);

β^b_m: column vector of the *mth* coefficient of the production in industry *m* induced by new sewage plant construction(ex);

$I^b(t)$: total investment in new sewage plant construction at time *t* (ex);

β^d_m:column vector of the *mth* coefficient of the production induced in industry *m* by new sewage sludge plant construction(ex);

$e^t(t)$: column vector of net export at time *t* (en);

Gross regional product

$$GRP(t) = \sum_m v^m \cdot X^m(t) \quad ...(34)$$

ν : row vector of the *mth* element, (the rate of added value in the *mth* industry (ex));

X(t): the column vector of the *mth* element (the total product of industry *m* in the target area at time *t*(en));

$v^m \cdot X^m(t)$: economic add value of industry *m* at time *t*;

Case study

Studied area

The area studied is Beijing, the capital of China. The area of Beijing is 16.4 thousands square kilometers, with 19 million inhabitants in 2010. In the past decade, the rate of GRP growth annual is about 15% [37]. Due to its rapid economic and population growth, Beijing's municipal sewage emissions are increasing each year. In 2010, more than 1.4 billion tons of sewage emission was produced[38]. Many sewage treatment plants, constructed by the Beijing municipal government, have adopted advanced technologies, and the sewage treatment rate increased to 80% in 2010[39]. However, there is still about 270 million tons sewage without treatment. The untreated sewage produces secondary pollution to water environment. Recently, an increasing attention on environment protections has been aroused by the government. Accordingly, The Twelfth Five-Year Plan of Economic and Social Development of Beijing requires that all sewage be treated and load of COD be reduced by 8.7% in 2015, compared with 2010[40]. Therefore, the policy new sewage plant construction was adopted.

Data

Three types of data are used in this study. One portion includes published data pertaining to population growth, investment, GRP, economic output values, the amount of sewage, as well as sewage sludge discharge and treatment. The data of population growth, investment, and GRP can be obtained from Beijing Statistical Yearbook 2011[37]; the data of economic output values from Beijing input-output extension table 2010[41]; the data of amount of sewage from Beijing Water Resources Bulletin 2011 [42]. Another portion is composed of survey data, which include detailed information about sewage treatment technologies. The technical data of sewage treatment are based on sewage treatment plants located in Beijing. The third portion is composed of calculated data based upon the published data, such as the coefficient of water pollutant emissions and the coefficient of discharged sewage pollutant emissions.

Technology

In this simulation, three types of MBRs technology are used, which are conventional MBR, dynamic membrane bioreactor (DMBR) and ultrasonic membrane bioreactor (UMBR). Three types of conventional activated sludge technology are employed as well which are anaerobic-anoxic-oxic (A/A/O), sequence batch reactor (SBR) and oxidation ditch (OD). Detailed information about these technologies is presented in Tables1 and 2.

Case setting

In this study, there are three scenarios (Table 3). The reduction rate of water pollutant, energy consumption intensity and GHG emission are defined as the percent decrease of the water pollutant emissions, energy consumption intensity and GHG emission level in 2020, respectively, compared with 2010. Beijing government gives subsidy for construction of new sewage plant. Scenario 1 simulates the situation of no new sewage plant construction. Scenario 2 simulates the implementation of new sewage plant construction with the introduction of conventional activated sludge technologies. Scenario 3 shows the simulations of new sewage plant construction with the introduction of MBRs technologies. Accordingly, the reduction rate of water pollutants, energy consumption intensity and GHG emission intensity are set as 15%, 34% and 36% respectively, and annual subsidy for construction of new sewage plant as 1 billion[38].

RESULTS

Sum of GRP for ten years

The ten years' sum of GRP for Scenario 1, 2 and 3 are 19,707, 22,464 billion CNY and 22,713 billion CNY, respectively (Fig. 2). Based on the simulation results, economy grows significantly in Scenario 2 and 3 in which new sewage plants are constructed for reducing water pollutants. Moreover, ten years' GRP for Scenario 3 using MBRs technology is 249 billion CNY more than that of Scenario2 using original sewage treatment technologies.

Load of water pollutants

Load of T-P for ten years for Scenario 1, 2

Table 1. MBRs technology

Technology	Influent (mg/L)	Effluent (mg/L)	Construction cost (million CNY)	Operation cost (CNY/ ton)	Capacity of water treatment (million ton/ year)
Membrane Bioreactor (MBR)	T-P:6 T-N:65 COD:450	T-P:1 T-N:15 COD:30	50	2.20	18.25
Dynamic Membrane Bioreactor (DMBR)	T-P:6 T-N:65 COD:450	T-P:1 T-N:10 COD:15	165	3.00	36.50
Ultrasonic Membrane Bioreactor (UMBR)	T-P:6 T-N:65 COD:500	T-P:1 T-N:8 COD:50	70	3.60	10.95

Table 2. Conventional activated sludge technologies

Technology	Influent (mg/L)	Effluent (mg/L)	Construction cost (million CNY)	Operation cost (CNY/ ton)	Capacity of water treatment (million ton/ year)
Anaerobic-Anoxic-Oxic (A/A/O)	T-P:6 T-N:65 COD:450	T-P:2 T-N:26 COD:81	80	0.70	36.50
Sequence Batch React (SBR)	T-P:6 T-N:65 COD:450	T-P:2 T-N:30 COD:90	80	0.60	36.50
Oxidation Ditch (DO)	T-P:6 T-N:65 COD:450	T-P:2 T-N:31 COD:90	60	0.75	36.50

Table 3. Scenario composition

Scenarios	Water pollutant reduction rate	Energy consumption intensity reduction rate	GHG emission intensity reduction rate	Subsidy for construction of new plants with conventional activated sludge technology	Subsidy for construction of new plants with MBRs technology
Scenario 1	15%	34%	36%	without	without
Scenario 2	15%	34%	36%	with	without
Scenario 3	15%	34%	36%	without	with

and 3 are 49,077, 47,642 and 46,214 tons respectively; load of T-N for ten years for Scenario 1, 2 and 3 are 536,073, 535,963 and 533,242 tons respectively; load of COD for ten years for Scenario 1, 2 and 3 are 1,693,265, 1,218,698 and 1,007,074 tons respectively (Fig. 3). Load of T-P, T-N and COD for Scenario 3 which constructs new sewage plants using MBRs technology is lower than that of Scenario 1 where no new plants are construct and that of Scenario 2 where new sewage plants are constructed using original technologies. These simulation results demonstrate that MBRs technology are more efficient to improve water environment than original technologies.

Energy consumption intensity in 2020

According to the plan of Beijing government[40], a 34% reduction of energy consumption intensity (with energy consumption intensity is less than 32,625 TCE/ billion CNY in 2020) in 2020 was set up, compared with that of 2010. Energy consumption intensities for Scenario 1, 2 and 3 are 25,194, 31,909 and 31,834 TCE/ billion CNY respectively, which are lower than the energy consumption intensity target value in 2020 (Fig. 4). Although energy consumption of MBRs technology is as the twice demand of conventional activated sludge technology[12], the reduction target of energy consumption intensity in 2020 is achievable for Scenario 3. However, it should be noted that the lowest energy consumption intensity in 2020 is obtained in Scenario 1, as the constraint of water pollutants load is much strictly than the energy consumption intensity in this research. In scenarios 2 and 3, where an emission constraint imposed by 15% reduction, the results of the more production and energy consumption are resulted from the installation of new wastewater treatment plants, which dispose of more water pollutants and

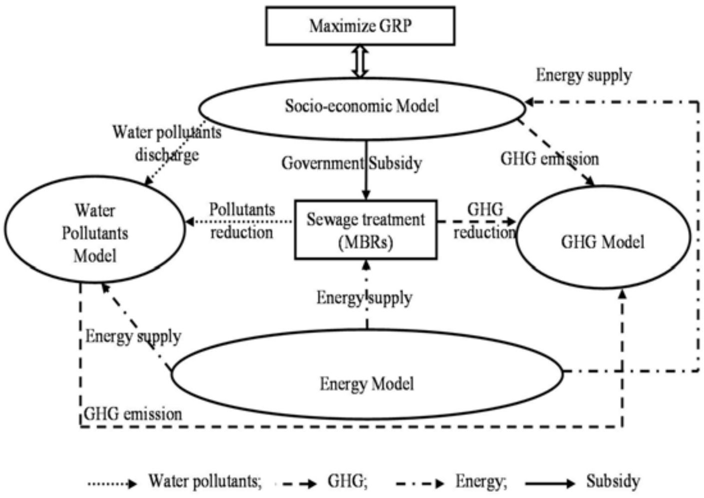

Fig. 1. Framework of the model

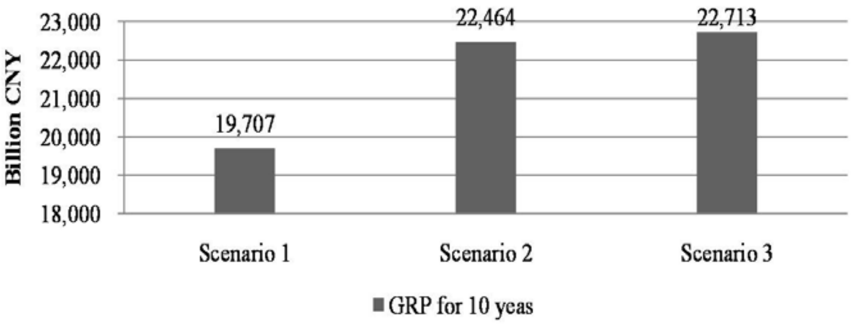

Fig. 2. Framework of the model

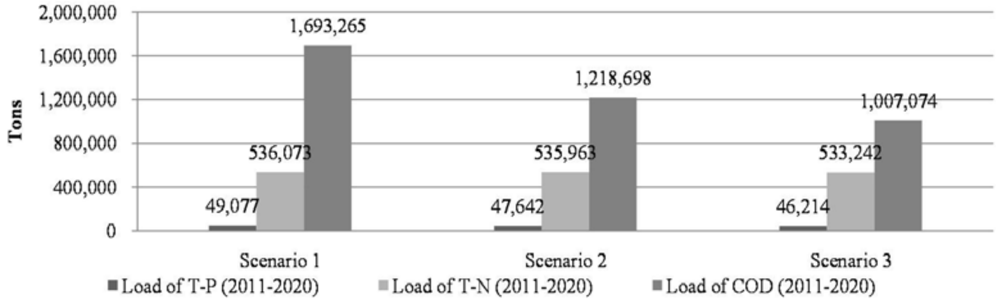

Fig. 3. Total net load of water pollutants for 10 years for every scenario

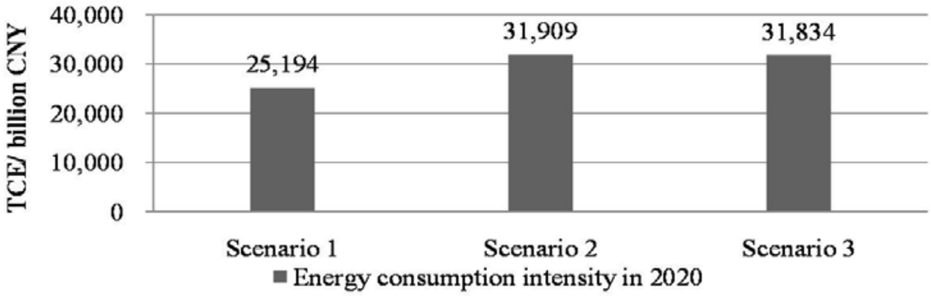

Fig. 4. Energy consumption intensity in 2020 for every scenario

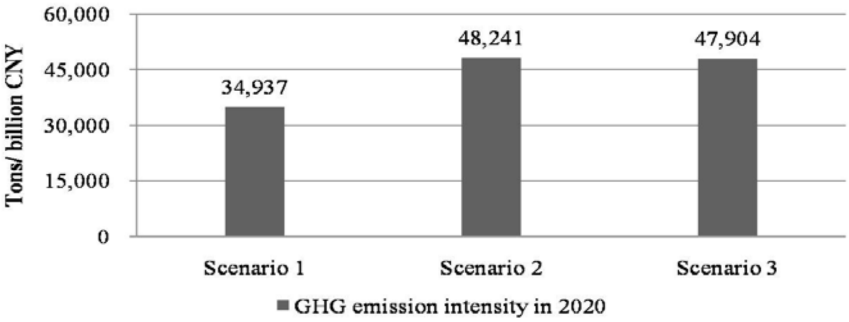

Fig. 5. GHG emission intensity in 2020 for every scenario

allow industries not only more productions but also more water pollutants emissions.

GHG emission intensity 2020

GHG emission is determined by energy consumption. GHG emission intensity for Scenario 1, 2 and 3 is 34,937, 48,241and 47,904 tons/ billion CNY, respectively (Fig. 5). The GHG emission reduction target in 2020 is achievable for every scenario (according to Beijing government's plan, GHG emission intensity in 2020 should be less than 49,953 tons/ billion CNY)[40]. Noticeably, the lowest GHG emission intensity in 2020 is gained in Scenario 1, as the constraint of water pollutants load is much strictly than GHG emission intensity in this research. In particular, the simulation results forecast a lower value of GHG emission intensity for Scenario 3 with MBRs technology, than that of Scenario 2 with original technologies.

DISCUSSION

Considerations of choosing a wastewater treatment technology should include not only cost, but also its related effects on other industries. The capital and running cost of MBRs are usually higher than that of conventional activated sludge treatment technologies[21, 23]. Our results, however, show that the monetary input in MBRs contributed to GRP growth more than that of other conventional activated sludge techniques did.

It is assumed that the subsidies for new installation of wastewater treatment plants are the same in all scenarios, i.e.10 billion CNY for ten years. The results represent that GRP for scenario 2 and scenario 3 are increased by 2,757 and 3,006 billion CNY, respectively, compared with that of scenario 1. It indicates that: conventional activated sludge and MBRs are economic efficient, and the efficiency of investment of MBRs is higher than that of the conventional activated sludge.

In scenario 2, the reduction rates of T-P, T-N and COD in 2020 compared with 2010 are 19%, 15% and 54%, respectively. In scenario 3, the reduction rates of T-P, T-N and COD in 2020 compared with 2010 are 22%, 15% and 66%, respectively. The prospective T-N reduction rates are the same as the target set in two scenarios, resulting from the inefficient in T-N removal in conventional activated sludge and MBRs. Therefore, T-N reduction rate is able to be used as a ruling parameter to control the loads of T-P and COD the process of sewage treatment at the same time. This finding is similar to[30, 32, 35].

Summarily, MBRs is suitable for wastewater treatment since it has outstanding pollutant removal rate, and our results also demonstrated that MBRs is economic efficient as well. However, it is should be noted that an advanced technology or an integrated policy is required if we try to reduce more water pollutants and make two of the other reduction goals accomplishable.

CONCLUSIONS

In this study, a comprehensive linear model and computer simulation is established to analyze the socio-economic and environmental impact of membrane bioreactors in sewage treatment. The following conclusions are drawn by the simulation results.

(i) MBRs technology requires higher investment and running cost. However, it is economic efficient as the wastewater treatment method for the new plants.

(ii) T-P, T-N and COD in 2020 can be reduced by 22%, 15% and 66%, respectively, using the treatment of MBRs, compared to those of 2010. Accordingly, the installation of new MBR plants is relatively superior to conventional activated sludge plants on environmental performances.

(iii) Energy consumption of MBR is twofold of the conventional activated sludge treatment approaches. However, reduction of energy consumption and GHG emission is achievable by introducing MBRs with the target of wastewater pollutants reduction rate of equal 15%.

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