Environmental impacts of resource recovery from wastewater treatment plants

Hao, Xiaodi; Wang, Xiangyang; Liu, Ranbin; Li, Shuang; van Loosdrecht, Mark C.M.; Jiang, Han

DOI
10.1016/j.watres.2019.05.068

Publication date
2019

Document Version
Final published version

Published in
Water Research

Citation (APA)
Hao, X., Wang, X., Liu, R., Li, S., van Loosdrecht, M. C. M., & Jiang, H. (2019). Environmental impacts of resource recovery from wastewater treatment plants. *Water Research*, *160*, 268-277. https://doi.org/10.1016/j.watres.2019.05.068

Water Research 160 (2019) 268–277

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Environmental impacts of resource recovery from wastewater treatment plants

Xiaodi Hao [a, *], Xiangyang Wang [a], Ranbin Liu [a], Shuang Li [b], Mark C.M. van Loosdrecht [a, c], Han Jiang [b]

[a] Sino-Dutch R&D Centre for Future Wastewater Treatment Technologies/Beijing Advanced Innovation Center of Future Urban Design, Beijing University of Civil Engineering & Architecture, 1 Zhanlanguan Road, Xicheng District, Beijing, 100044, PR China
[b] Beijing Capital Co., Ltd, 21 Chegongzhuang Street, Xicheng District, Beijing, 100044, PR China
[c] Dept. of Biotechnology, Delft University of Technology, van der Maasweg 9, 2629, HZ Delft, the Netherlands

ARTICLE INFO

Article history:
Received 3 March 2019
Received in revised form
23 April 2019
Accepted 21 May 2019
Available online 25 May 2019

Keywords:
Wastewater treatment plants (WWTPs)
Resource recovery
Environmental impacts
Life cycle assessment (LCA)
Thermal energy
Net-zero impact

ABSTRACT

Conventional wastewater treatment plants (WWTPs) clean wastewater and minimize water pollution; but, while doing so, they also contribute to air pollution and need energy/material input with associated emissions. However, energy recovery (e.g. anaerobic digestion) and resource recovery (e.g. water reuse) allow us to offset the adverse environmental impacts of wastewater treatment. Life cycle assessments (LCA) have been used more and more to evaluate the environmental impacts of WWTPs and to suggest improvement options. There is a need to search for resource recovery applications that genuinely realize a net-zero impact on the total environment of WWTPs. In this work, a scheme with highly efficient energy and resource recovery (especially for thermal energy) is proposed and evaluated. The environmental impact of a conventional WWTP in comparison with the scheme proposed here, with energy/resource recovery included, was calculated, and discussed with reference to LCA methodology. In the process of using LCA, it was necessary to choose a regional situation to focus on. In this case, a Chinese situation was focused as a reference, but the qualitative information gained is of worldwide relevance. The results clearly revealed that conventional WWTP does not benefit the total environment as a whole while the new scheme benefited the total environment via resource/energy recovery-based processes. Among others, thermal energy recovery played a significant role towards a net-zero LCA analysis (contributing around 40%) which suggests that more attention and research should be focused on it.

1. Introduction

Biological wastewater treatment is an effective technology to remove oxygen demanding compounds (COD) and nutrients (N and P) from wastewater. However, the role of wastewater treatment plants (WWTPs) is no longer merely constraint to protecting the aquatic environment (e.g. eutrophication) or solely evaluated based on the effluent quality. On the contrary, the holistic environmental impacts other than an aquatic environment have been highlighted in the construction and operation of WWTPs (Guest et al., 2009; Corominas et al., 2013; Teodosiu et al., 2016). For instance, emissions of greenhouse gasses (GHG) have been recognized as a major negative impact of WWTP operation (Kampschreur et al., 2009; Foley et al., 2010; Fang et al., 2016). The previous studies have explicitly demonstrated that the total environmental impacts of a typical WWTP is always negative (Corominas et al., 2013; Hellweg and Milà i Canals, 2014). WWTPs bring about a net global adverse impact on the environment when the external energy and chemical input and consumption are accounted for by Life Cycle Assessment (LCA) methods. Of course, the local improved water quality is the main driver for treating wastewater. According to estimations, the annual electricity input for WWTPs in the USA accounts for about 3% of the national total consumption (EIA, 2010). Apparently, the health of the aquatic environment is achieved at the sacrifice of other environmental compartments because of materials and energy consumption (Roeleveld et al., 1997; Corominas et al., 2013). From a holistic perspective, WWTPs could be considered to be a source of pollution rather than a barrier for emissions. This situation is becoming worse, along with increasingly stringent discharge standards, such as the campaign for upgrading and reconstruction

* Corresponding author.
E-mail address: xdhao@hotmail.com (X. Hao).

https://doi.org/10.1016/j.watres.2019.05.068
0043-1354/

of WWTPs in China (Hao, 2006; Zhu et al., 2013; Wang et al., 2015b).

In order to minimize the overall impact of wastewater treatment and put WWTP design and operation on a more sustainable track, several concepts and improvements have been proposed. For instance, energy balancing or carbon neutrality has been widely accepted as a concept and is already achieved in practice (Mo and Zhang, 2012; Gao et al., 2014; Hao et al., 2015; Wang et al., 2015a; Chen et al., 2018). These concepts highlight the energy-carrier feature of wastewater and the necessity of recovering energy. Anaerobic digestion, on the one hand, has long been a commonly applied process for extracting organic energy from wastewater in the form of biogas, which can be converted to electricity, green gas or thermal energy (Mo and Zhang, 2013; Tomei et al., 2015; Shiu et al., 2017). However, organic energy is effectively barely enough to meet the energy demand of a WWTP. The harvested energy via anaerobic digestion can only harvest around 10% of the total energy in wastewater (Shizas and Bagley, 2004; Heidrich et al., 2011; Hao et al., 2015, 2018). Nutrient (N and P) recovery from wastewater is another pathway to offset the adverse environmental impacts. However, more efficient recovery processes or high value-added products are yet to be found if we are to achieve a full trade-off with energy/resource consumption (Mo and Zhang, 2013). Thus, further research into alternative energy/resource recovery pathways is warranted.

Thermal energy recovery from wastewater has largely been ignored, but it may contribute significantly to offsetting the adverse environmental impacts of WWTPs (Hao et al., 2018). Wastewater has a substantial thermal energy potential and is an excellent heat resource for effective and economical operation of heat pumps. The heat recovered in-situ is the best option, as where the treatment plant itself needs much heat, such as sludge drying (Niemela and Saarela, 2009; Eneco Delft, 2010; Nowak et al., 2015; Kollmann et al., 2016), or is positioned close to an area that needs heating/cooling energy. An evaluation of heat recovery on the environmental impact of a WWTP is still lacking.

In recent years, LCA has been applied to evaluate the impact of WWTPs on the environment (Lundin et al., 2004; Pasqualino et al., 2009; Loubet et al., 2014) as well as to suggest improvement options (Buonocore et al., 2016; Remy et al., 2016), including both domestic and industrial wastewater (Vlasopoulos et al., 2006). In China, LCA studies often use some foreign normalized benchmark values and weights for calculation, which produce results that often deviate from Chinese conditions (Chen et al., 2003; Huang et al., 2014; Wang et al., 2015b; Gallego-Schmid and Tarpani, 2019).

In this study, the current LCA framework was adapted for Chinese conditions by localizing the normalization factors and relative weights. This allowed the regional impact of wastewater discharge to be calculated. With this LCA approach, the overall environmental impacts of a WWTP in China were evaluated and compared to potential resource/energy recovery options, particularly highlighting thermal energy recovery. It was expected that the present work can ascertain the effect of the thermal energy recovery on improving the impact of WWTPs on the total environment.

2. LCA methodology

Based on the existing standard LCA models (ISO, 2006a; ISO, 2006b; Goedkoop et al., 2009), some adjustments were made to improve and optimize the accuracy by localizing normalization factors and relative weights to the Chinese situation.

2.1. Goal and scope definition

The targeted municipal WWTP consists of two parallel biological wastewater treatment lines (an oxidation ditch and a 5-stage Bardenpho process) and a combined sludge treatment line. The plant is located in Changzhi City, Shanxi, China. The first wastewater line receives 59,200 m^3/d (designed inflow: 100,000 m^3/d) and the second line handles 91,500 m^3/d (designed inflow: 100,000 m^3/d). The secondary effluent from the parallel treatment lines is merged prior to tertiary treatment and discharge as the final combined effluent (COD = 18 mg/L, BOD_5 = 4 mg/L, SS = 6 mg/L, TN = 13 mg N/L, NH_4^+ = 0.6 mg N/L and PO_4^{3-} = 0.3 mg P/L). Both treatment lines have an identical service term of 20 yrs. In the wastewater treatment lines, P removal is enhanced by dosing chemicals (poly-aluminum chloride and polyacrylamide) in a high-efficiency fiber filtration process on the effluent flow. The plant must meet the Discharge Standard Class I-A of China (GB 18918-2002, 2002: COD = 50 mg/L, BOD_5 = 10 mg/L, SS = 10 mg/L, TN = 15 mg N/L, NH_4^+ = 5 mg N/L and PO_4^{3-} = 0.5 mg P/L). Excess sludge is after dewatering transported outside the plant for landfilling disposal (a distance of 6 km from the plant). The function unit (FU) used in this study is defined as person equivalent (p.e.) for a period of 1 year, which is most commonly used in similar studies (Lundin et al., 2000; Hospido et al., 2004), that is, 1 FU = 1 PE•a. According to the Chinese standard (GB 50014-2006, 2016), the wastewater volume per PE was set at 0.1 m^3/d in this study.

2.2. Scenario construction

The base-case scenario covers the construction, operation, and demolition stages of the targeted WWTP (Pennington et al., 2004; ISO, 2006b). All of the energy/materials input/output between the influent and effluent were considered in the LCA application (Fig. 1a). In contrast, the resource recovery scenario was a proposed plant with highly efficient resource/energy recovery, as shown in Fig. 1b. The tertiary effluent was firstly used for heat exchange by water source heat pump (WSHP) and then reused for industrial cooling water in nearby power plants. The harvested heat can be used for sludge drying inside in the WWTP as well as air conditioning. Instead of landfilling as in base-case scenario, the sludge in the resource recovery scenario was transported to an incineration plant with thermal energy recovery and electricity production capabilities. Finally, phosphorus can be recovered from incineration ash, following which the abstracted ash can be used in construction materials (Lynn et al., 2018; Świerczek et al., 2018).

2.3. Inventory analysis

Life cycle inventory (LCI) data was collected from operating reports for existing processes and databases. The inventory data on materials or energy input and environmental discharge during construction, operation, and demolition was obtained from the internal data of the assessed plant (see Table S1, supplementary information). Background inventory data was obtained through the Chinese Life Cycle Database (CLCD) (IKE, 2010) that contains unit process data that is mainly valid for Chinese markets. In the assessment, calculations methods of carbon emissions from wastewater treatment and sludge treatment/disposal (landfill and incineration) are also based on the literature (Monteith et al., 2005; IPCC, 2006; Yang, 2013). Among others, input in the demolition phase is mainly for energy consumption: 95 kW·h/m^2 (approximately 90% of the total energy consumption in the construction phase, Liu, 2010). During the demolition process, removed rebar could be recycled and remaining concrete would become waste; the average recovery efficiency of removed rebar is 0.38 t/t in China (Gao et al., 2016); recycled rebar can offset consumption of building materials in a new construction phase. Thus, the impact of recycled rebar on the environment is included in this assessment.

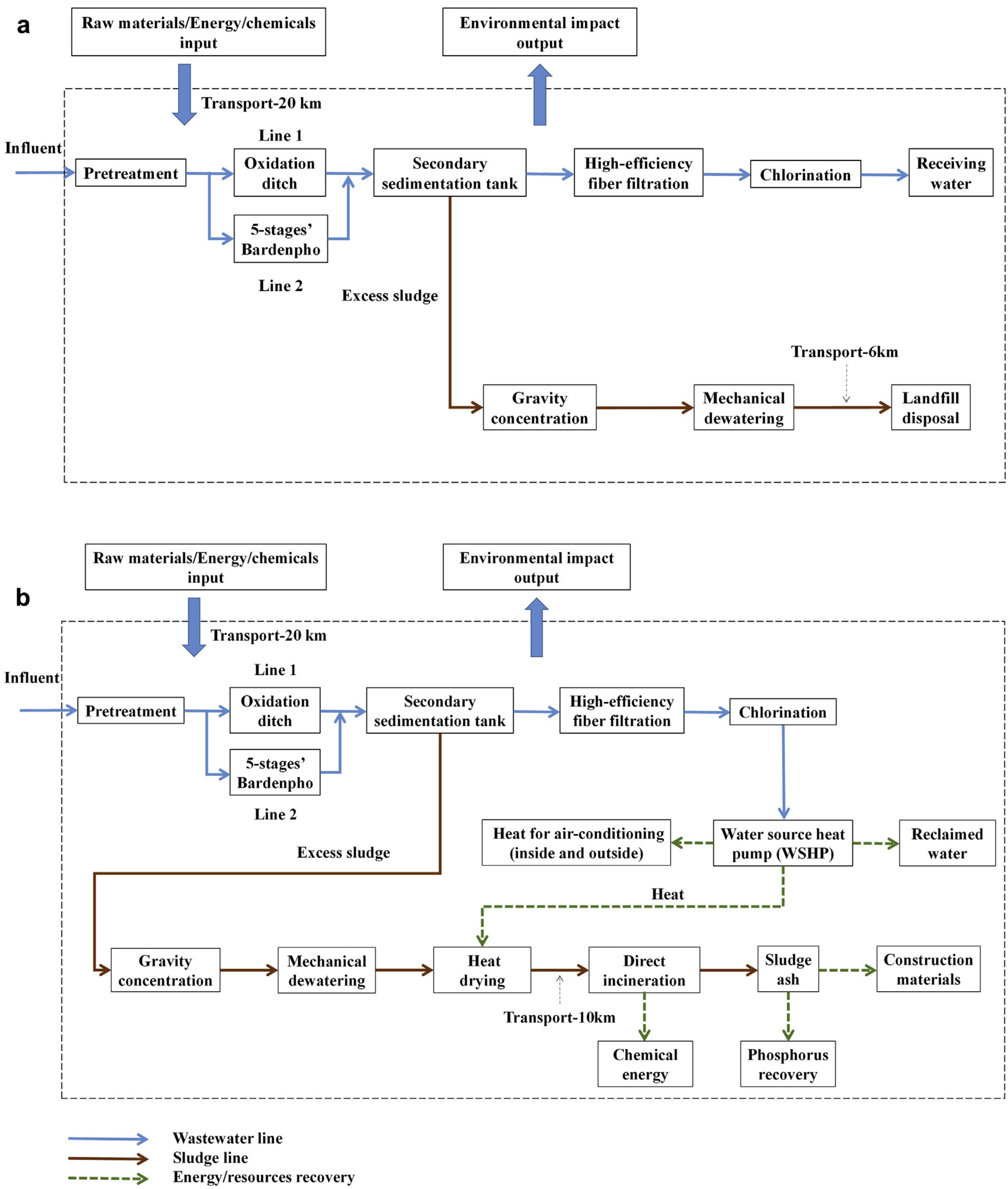

Fig. 1. Boundaries of the assessed WWTP with and without energy/resource recovery.

The calculation regarding the involved resource/energy recovery was based on previous studies (Hao et al., 2015, 2018, 2019; Xu, 2015; Alyaseri and Zhou, 2017; Amann et al., 2018). Among others, Egle et al. (2015) and Amann et al. (2018) indicated that recovered P resource from sewage sludge ash (SSA) exhibited a higher potential for P recovery (70–90% of P at the WWTP's inlet, 80% in this study) than direct recovery at the wastewater treatment plant. The related data (see Table S1) about the supplemented facilities for the resource/energy recovery in both construction and demolition phases was estimated according to the existing literature (Jossa and Remy, 2015; Egle et al., 2015; Alyaseri and Zhou, 2017; Amann et al., 2018; McQuay, 2018). The base-case scenario can meet the needs of the standards for effluent reuse, and so no extra facilities will be needed. In practice, Hao et al. (2018) indicated that WSHP could recover thermal energy (4 °C temperature difference) for heating with 1.77 kW·h/m^3 (net energy production), which was adopted in this study. Incineration can completely destroy organic substances (minimizing landfilling) and generate electricity with 0.5 kW·h/m^3 (Hao et al., 2019), which was also adopted in this study. All detailed data inventory is listed in Table S1.

2.4. Impact assessment

The Life Cycle Impact Assessment (LCIA) is a crucial part of the LCA process. At present, there is no generally accepted assessment approach, due to its complexity and difficulty (Pennington et al., 2004; Dreyer et al., 2008). Generally accepted LCIA approaches are Environmental Design of Industrial (EDIP) from Denmark, Life Cycle Assessment-An Operational Guide to the ISO Standards 2001 (CML2001) from the Environmental Research Center of Leiden University, and the Ecological Index Method Eco-indicator 99 and Environmental Priority Strategies in Product Development (EPS) from Sweden (Dreyer et al., 2008; Luo et al., 2013), respectively. This study used LCA method CML2001, with adaptations to make it suitable for the Chinese context.

2.4.1. Classification

Based on the available data from the plant, important indicators for the environmental impacts that are considered in the study are presented in Table S2 at a mid-point level (Goedkoop et al., 2009; Yang, 2013). Indicators include global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), abiotic resources depletion potential (ADP), human toxicity potential (HTP), black and odor potential (BOP), landfill space depletion potential (LSD), and Freshwater use (FWU) respectively. Among others, BOP is not a necessary impact category defined in standard LCA methods, but it could reflect an urgent water pollution problem in China, and is therefore included in this assessment.

2.4.2. Characterization

According to the classification of the environmental impacts, characterization factors (CF) can be used to calculate the environmental burden (EB) (Gallego-Schmid and Tarpani, 2019). EB is a weighted summation of the individual environmental impact factors (Eq. (1)). Among others, the calculation of BOP and LSD was based on the previous literature (Deng and Wang, 2003; Liang, 2012) by Eq. (2) and Eq. (3), respectively.

$$EB = \sum_{i=1}^{n} m_i CF_i \tag{1}$$

$$BOP = m_{COD} CF_{COD} + m_{NH_4{}^+} CF_{NH_4{}^+} \tag{2}$$

$$LSD = \sum_{i=1}^{n} m_i / D_i \tag{3}$$

Where: i is the kinds of chemical substances contained in all the emission substances; n is the total number of impact substances in the emission substances; m_i is the mass of “i” substance in the inventory analysis; CF_i is the characterization factor of the impact caused by “i” substance on each environmental category; m_{COD} is the biodegradable COD; D_i is the average waste density.

2.4.3. Quantification

Normalization Environmental Burden (NEB) can be evaluated from EB values compared to local benchmark values, and relative values after comparison are usually taken (EC-JRC, 2010; Liang, 2012). For the Chinese situation, localizing the benchmark values were conducted before normalization. The GWP benchmark value was calculated according to China's average annual CO_2 emissions per capita (the “Global Carbon Project”, Peters et al., 2015); the ADP benchmark value was calculated according to China's consumption data on energy (2012 BP World Energy Statistics Yearbook, BP Group, 2013); the EP, BOP, AP, LSD, and FWU benchmark values were calculated based on the statistical data (National Bureau of Statistics, 2018; Ministry of Ecology and Environment, 2018); HTP benchmark values were still based on the CML2001-Nov. 2010 evaluation standard system (Huppes and van Oers, 2010). All of these benchmark calculations take their data from the same year (2010).

The Analytic Hierarchy Process (AHP) was applied to calculate weighting values. AHP is a practical, multi-criteria, and decision-making method. The process of AHP is to simplify complicated environmental problems into different combination factors, according to the nature of the problem and the objectives to be achieved, and then to form a top-down dominating relationship (Liang, 2012; Yang, 2013). The structuring process of the judgment matrix was divided into two steps: i) scaling importance (based on Table S3) and testing logical consistency, according to the relative importance between the two-two comparison of different environmental impacts (Liang, 2012; Yang, 2013); ii) calculating weighting values (W). According to the importance of the different environmental impacts from Table S4, the literature and also local WWTPs (Liang, 2012; Vera et al., 2015; Zhao et al., 2018), the relative importance of the different environmental impacts can be expressed in a judgment matrix, as shown in Table S4.

To make the judgment matrix logical, it is necessary that its consistency is properly checked. A calculation indicates that the consistency index CR (consistency ratio) of the matrix A is equal to 0.08 (CR < 0.1), demonstrating that the judgment matrix A is logical in its consistency. The scaled matrix can be normalized according to its columns (Eq. (4)), and the normalized matrix is as follows (Eq. (5)):

$$\overline{a_{ij}} = \frac{a_{ij}}{\sum_{k=1}^{7} a_{kj}}, \ i, j = 1, 2\& 7 \tag{4}$$

$$\begin{bmatrix} 0.339 & 0.437 & 0.311 & 0.320 & 0.284 & 0.252 & 0.221 & 0.207 \\ 0.113 & 0.146 & 0.311 & 0.107 & 0.142 & 0.151 & 0.110 & 0.172 \\ 0.169 & 0.073 & 0.156 & 0.320 & 0.284 & 0.252 & 0.257 & 0.069 \\ 0.113 & 0.146 & 0.052 & 0.107 & 0.142 & 0.151 & 0.110 & 0.172 \\ 0.085 & 0.073 & 0.039 & 0.053 & 0.071 & 0.101 & 0.147 & 0.103 \\ 0.068 & 0.049 & 0.031 & 0.036 & 0.036 & 0.050 & 0.110 & 0.069 \\ 0.056 & 0.049 & 0.022 & 0.036 & 0.018 & 0.017 & 0.037 & 0.172 \\ 0.056 & 0.029 & 0.078 & 0.021 & 0.024 & 0.025 & 0.007 & 0.034 \end{bmatrix} \tag{5}$$

Then, adding each line (Eq. (6)), normalizing it (Eq. (7)), and finally getting a vector (Eq. (8)):

$$\overline{W_i} = \sum_{j=1}^{7} \overline{a_{ij}} \tag{6}$$

$$W_i = \frac{\overline{W_i}}{\sum_{i=1}^{7} \overline{W_i}} \tag{7}$$

$$W = [0.296 \quad 0.157 \quad 0.198 \quad 0.124 \quad 0.084 \quad 0.056 \quad 0.051 \quad 0.034] \tag{8}$$

Eq. (8) presents the weighting values of every environmental impact in the total environment for the assessed plant.

Finally, the total environmental impact value of WWTPs can be calculated according to Eq. (9), with which final results can be used to assess the impacts of different WWTPs on the total environment.

$$LCIA = \sum_{i}^{n} W_i NEB_i \tag{9}$$

Where: LCIA is the total index value of life cycle impact assessment; W_i is weighting values of environmental impacts; and NEB_i is the normalized environmental burden.

3. Results and discussion

3.1. Environmental impact of base-case scenario

3.1.1. Characteristic results and analysis

According to the standard LCA methods, all the characteristic results for the same environmental impact have to be transformed into their equivalent units. Based on the statistical analysis, the environmental impacts (caused by material consumption, energy consumption, and direct environmental emissions) can be calculated according to one unit of FU (1 PE•a), to meet the need of the Discharge Standard Class I-A, as shown in Table 1.

The relative contributions of different phases of the plant's life cycle to the different environmental impacts are shown in Fig. 2. The environmental impact is largely (most around 90%) derived from the operational phase of the treatment plant (Fig. 2). These results are consistent with previous studies (Foley et al., 2010; Pasqualino et al., 2010). The environmental impacts for Line 1 and Line 2 are roughly similar, but ADP from Line 2 was higher due to the complicated Bardenpho process which resulted in higher consumptions of both materials and energy in construction.

3.1.2. Normalization results and analysis

The normalization factors and normalized results for the Chinese context are listed in Table S5. As shown in Table S5, global warming potential (GWP) and landfill space depletion potential (LSD) accounted for the highest environmental impacts, while eutrophication potential (EP) and human toxicity potential (HTP) had the lowest environmental impact. The normalized environmental impacts indicate that the magnitude of GWP is the same as for BOP. Although the total amount of GWP is larger, its contribution to the total environmental impact index is actually comparable to that of BOP (Table S5). The effluent quality has a reverse relationship with the greenhouse impact; if the discharge standard continues to be upgraded, BOP and EP would certainly decline, but GWP and other environmental impacts would increase sharply, an effect that is consistent with other studies (Zhu et al., 2013; Wang et al., 2015b).

3.1.3. Total environmental impact

The normalized environmental impacts shown in Table S5 can be expressed as row vectors, as below:

$$A_1 = [0.01 \quad 1.44\times10^{-12} \quad 0.01 \quad 3.33\times10^{-5} \quad 2.22\times10^{-12} \quad 4.64\times10^{-3} \quad 0.14 \quad 1.29\times10^{-4}] \tag{10}$$

$$A_2 = [0.01 \quad 1.44\times10^{-12} \quad 0.01 \quad 3.63\times10^{-5} \quad 2.67\times10^{-12} \quad 4.65\times10^{-3} \quad 0.17 \quad 1.34\times10^{-4}] \tag{11}$$

By calculating $A_1 \times W$ and $A_2 \times W$ (W is the relative weight of the environmental impact, which is described in Section 2.4.3), the total environmental impact indexes of the two treatment lines are calculated respectively at $LCIA_1 = 0.0118$ and $LCIA_2 = 0.0132$ per FU.

Obviously, the plant does not benefit the total environment, in which Line 2 has a larger impact than Line 1, mainly due to the longer wastewater treatment process of Line 2. Currently, the plant consumes electricity generated from coal, and so increasing energy consumption would inevitably lead to increasing the environmental impacts, including indirect greenhouse gas emissions, atmospheric acidification, and depletion of non-renewable resources caused by electricity generation. For the foreseeable future, China will be reliant on coal-derived electricity.

Without resource/energy recovery involved in WWTPs, it is really difficult to acquire a “net-zero” impact or even to create a benefit on the total environment impact index. To make the WWTPs approach to the “net-zero” impact and/or to benefit of WWTPs on the total environment the contribution of potential resource/energy recovery need to be included in the assessment.

3.2. Environmental impact of resource recovery scenario

3.2.1. Characteristic results and analysis

The calculations for this scenario were identical to those for the base-case scenario (Section 3.1.1). After statistical analysis, the characteristic results of the resource recovery scenario are listed in Table 2. As shown in Table 2, some values in the operation phase appear negative, which also results in negative values, mostly for the total characteristic results. Clearly, the impacts of the resource/energy recovery on the total environment are significant, and the resource/energy recovery helps to reach a net benefit for the total environment.

3.2.2. Normalization results and analysis

The same normalization method was applied, as described in Section 3.1.2 (the relative weights of the environmental impacts have been given in Section 2.4.3). After the statistical analysis, the normalized environmental impacts of the resource recovery scenario are listed in Table S6.

To make a comparison, the normalized environmental impacts from the two processes are illustrated in Fig. 3. As shown in Fig. 3, the impact reduction of LSD on the environment is highly significant caused from the resource recovery scenario, in which the normalized environmental values are sharply reduced to 0.01 and 0.01 from 0.143 to 0.171, respectively for Line 1 and Line 2. Obviously, the large reduction in LSD is attributed to saving the landfill space by sludge incineration and ash utilization. Although the characteristic values (Fig. 3) of the resource recovery scenario still emerge as positive on EP, the normalized environmental impacts (1.43×10^{-12}) have become a very small share into the total environmental impact.

A comparison of the percent contributions of the two processes to each impact category is illustrated in Fig. 4. Clearly, the base-case scenario has only positive values on the environmental impacts (Fig. 4a; Fig. 4c), while the resource recovery scenario process creates some negative values (benefiting WWTPs), as shown in Fig. 4b and d. Phosphorus recovery (avoided mining) contributes to

Table 1
Characteristic results of the environmental impacts of the base-case scenario (1 FU = 1 PE·a).

Impact category	Construction		Operation		Demolition		Total	
	Line 1	Line 2	Line 1	Line 2	Line 1	Line 2	Line 1	Line 2
GWP (kg CO_2-eq/1 FU)	3.3	5.6	70.3	66.7	0.4	0.3	74.0	72.6
EP (kg PO_4^{3-}-eq/1 FU)	7.9×10^{-6}	1.9×10^{-5}	2.3×10^{-1}	2.3×10^{-1}	4.8×10^{-6}	6.7×10^{-6}	2.3×10^{-1}	2.3×10^{-1}
AP (kg SO_2-eq/1 FU)	1.5×10^{-2}	2.4×10^{-2}	2.2×10^{-1}	2.1×10^{-1}	1.8×10^{-4}	2.5×10^{-4}	2.3×10^{-1}	2.3×10^{-1}
ADP (kg Sb-eq/1 FU)	6.1×10^{-7}	1.2×10^{-6}	3.9×10^{-6}	3.7×10^{-6}	1.1×10^{-7}	1.2×10^{-7}	4.7×10^{-6}	5.1×10^{-6}
HTP (kg DCB-eq/1 FU)	1.4×10^{-6}	2.3×10^{-6}	5.7×10^{0}	6.9×10^{0}	5.2×10^{-10}	3.5×10^{-10}	5.7×10^{0}	6.9×10^{0}
BOP (kg COD-eq/1 FU)	5.2×10^{-4}	1.1×10^{-3}	1.5×10^{-1}	1.5×10^{-1}	1.9×10^{-8}	1.3×10^{-8}	1.5×10^{-1}	1.5×10^{-1}
LSD (m^3/1 FU)	4.8×10^{-8}	3.9×10^{-8}	3.2×10^{-2}	3.9×10^{-2}	2.6×10^{-3}	2.4×10^{-3}	3.5×10^{-2}	4.1×10^{-2}
FWU (kg/1 FU)	11.3	15.8	44.7	42.5	1.0	0.7	57.0	59.0

Note: Impact categories abbreviations: Global warming potential (GWP), Eutrophication potential (EP), Acidification potential (AP), Abiotic resources depletion potential (ADP), Human toxicity potential (HTP), Black and odor potential (BOP), Landfill space depletion potential (LSD), Freshwater use (FWU).

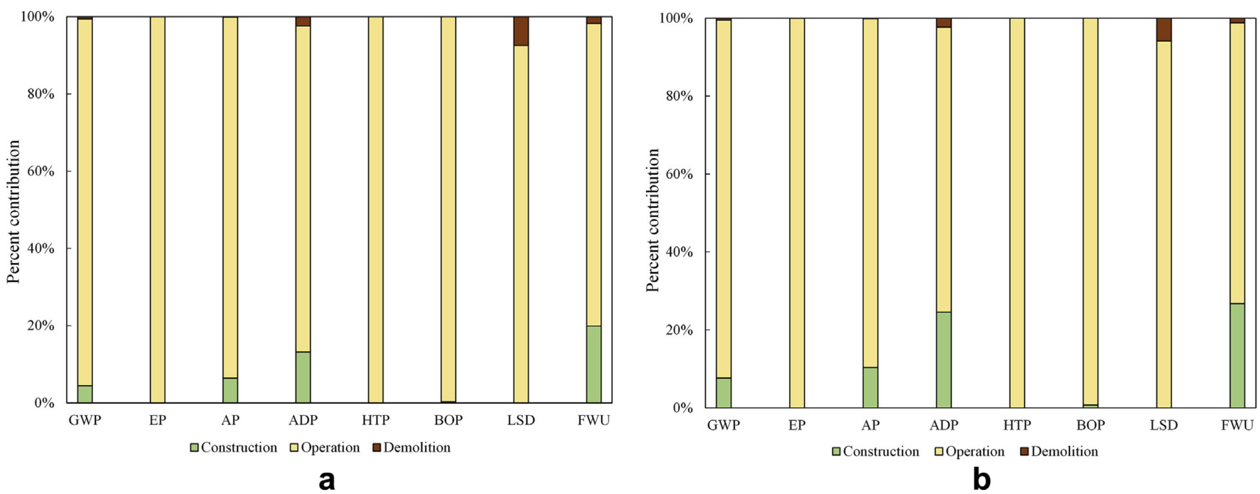

Fig. 2. Contributions of different phases to different environmental impacts in two lines of base-case scenario.

Table 2
Characteristic results of the environmental impacts of the resource recovery scenario (1 FU = 1 PE·a).

Impact category	Construction		Operation		Demolition		Total	
	Line 1	Line 2	Line 1	Line 2	Line 1	Line 2	Line 1	Line 2
GWP (kg CO_2-eq/1 FU)	3.4	5.7	−13.8	−20.2	0.4	0.3	−10.0	−14.1
EP (kg PO_4^{3-}-eq/1 FU)	1.3×10^{-5}	2.4×10^{-5}	2.3×10^{-1}	2.3×10^{-1}	5.0×10^{-6}	6.9×10^{-6}	2.3×10^{-1}	2.3×10^{-1}
AP (kg SO_2-eq/1 FU)	1.6×10^{-2}	2.5×10^{-2}	-6.7×10^{-1}	-6.8×10^{-1}	1.9×10^{-4}	2.5×10^{-4}	-6.5×10^{-1}	-6.6×10^{-1}
ADP (kg Sb-eq/1 FU)	6.7×10^{-7}	3.6×10^{-6}	-2.7×10^{-5}	-3.1×10^{-5}	1.1×10^{-7}	7.6×10^{-8}	-2.6×10^{-5}	-2.7×10^{-5}
HTP (kg DCB-eq/1 FU)	6.4×10^{-5}	8.9×10^{-5}	-8.9×10^{-5}	-9.0×10^{-5}	5.2×10^{-10}	3.5×10^{-10}	-2.6×10^{-5}	-1.4×10^{-6}
BOP (kg COD-eq/1 FU)	5.3×10^{-4}	1.1×10^{-3}	1.4×10^{-1}	1.4×10^{-1}	1.9×10^{-8}	1.3×10^{-8}	1.4×10^{-1}	1.4×10^{-1}
LSD (m^3/1 FU)	4.8×10^{-8}	3.9×10^{-8}	0×10^{0}	0×10^{0}	2.6×10^{-3}	2.4×10^{-3}	2.6×10^{-3}	2.4×10^{-3}
FWU (kg/1 FU)	1.2×10^{1}	1.7×10^{1}	-3.6×10^{4}	-3.6×10^{4}	1.0×10^{0}	6.8×10^{-1}	-3.6×10^{4}	-3.6×10^{4}

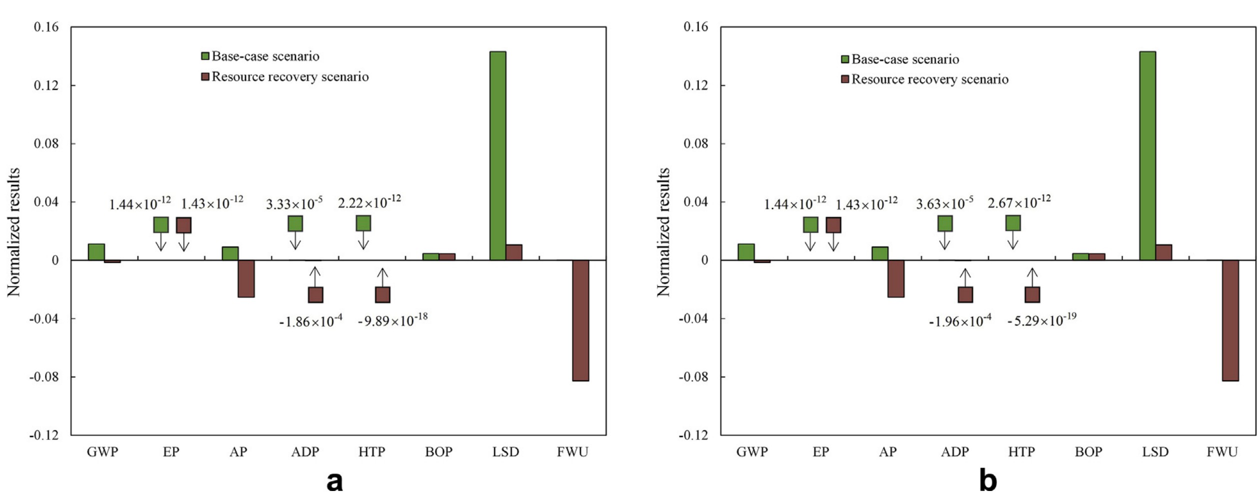

Fig. 3. Comparison of the normalized environmental results between the base-case scenario and the resource recovery scenario.

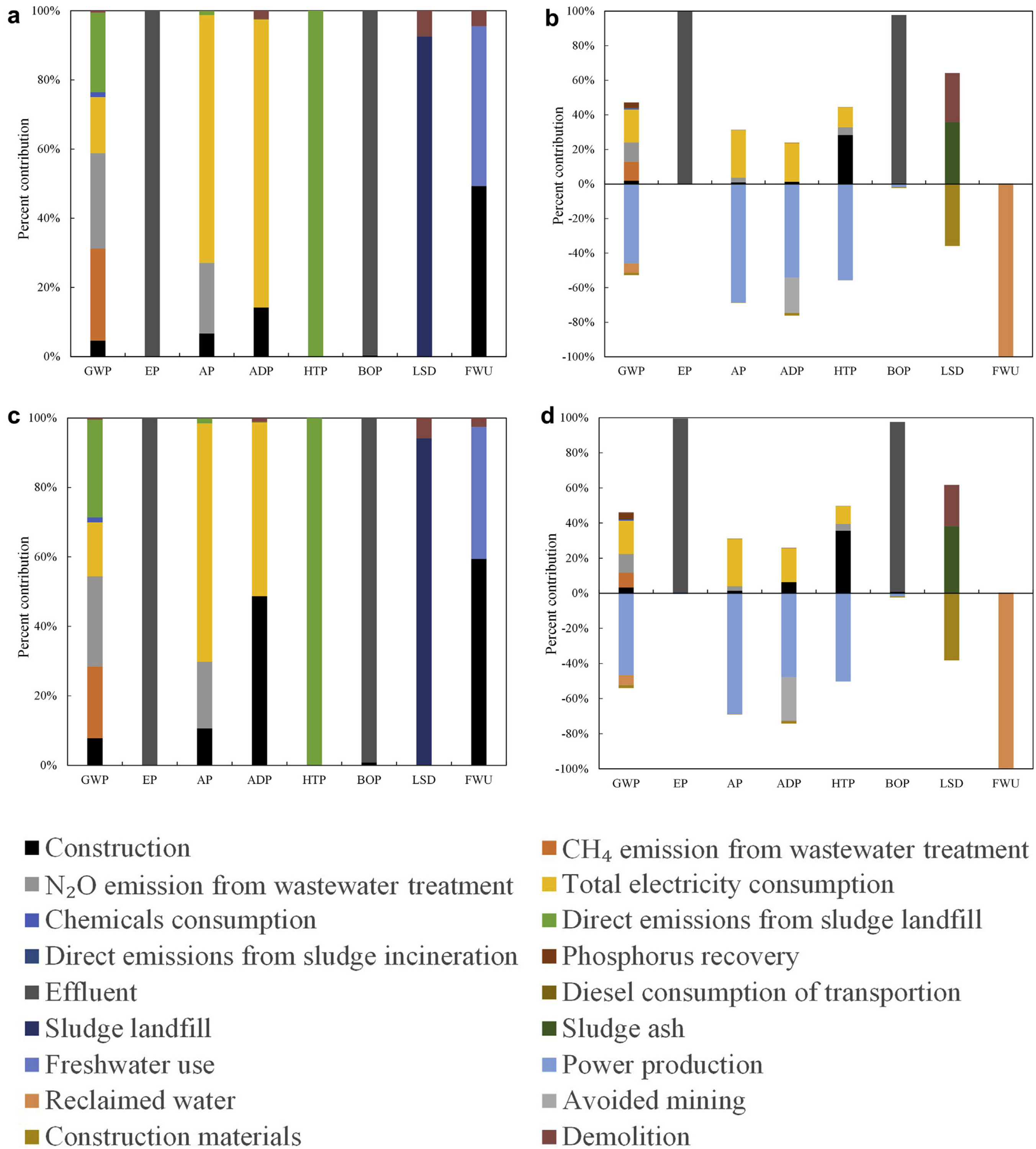

Fig. 4. Contributions of various processes to each impact category in two lines with two scenarios.

the reduction of the environmental impacts on ADP by 21% and 26%, respectively for Line 1 and Line 2, by saving phosphate rock mining. Ash utilization as construction materials (bricks and/or cement) also contributes significantly to the reduction (40% and 38%) of the environmental impacts on LSD, due to no sludge landfilling needed. Moreover, electricity generated by sludge incineration and thermal energy recovery by WSHP is responsible for reducing the environmental impacts on GWP, AP, ADP, and HTP by 46–77% (Fig. 4b; Fig. 4d). Even though both EP and BOP in the resource recovery scenario process still have positive values on the environmental impacts due to the pollutants from the effluent, the resource/energy recovery can offset these impacts on the total environmental.

3.2.3. Total environmental impact

Based on the new assessment, the indexes (LCIA) of the total environmental impact for the resource recovery scenario are calculated at $LCIA_1^{'} = -3.50 \times 10^{-3}$ and $LCIA_2^{'} = -3.72 \times 10^{-3}$ per FU, respectively for Line 1 and Line 2.

3.3. Comparison of base-case scenario and resource recovery scenario

Compared to the base-case scenario, the impacts of the resource recovery scenario on the total environment can both be reduced by 128–130%, in which the reduction of 100% is used to balance the impact (approaching to the net-zero impact on the total environment) and the remaining 28–30% is the benefit created by the resource recovery scenario on the total environment. The resource/energy recovery can indeed alter the total environmental impact, but greater benefits will be very difficult to attain unless electricity is supplied by such power sources as solar/wind/gas or nuclear energy.

As shown in Fig. 5, thermal energy recovery contributes to the largest share (38–41%) in the increased benefit, and organic energy recovery from sludge incineration is the second highest contributor to the increased benefit (30–33%). In contrast, incineration ash reuse for construction materials production only contributes marginally (5%) in the increased benefit, which is mainly due to the small amount of incineration ash. In China, organics (COD) in WWTPs influent is less than in other countries, so it is far from reaching net-zero environmental impact through organic energy recovery of conventional anaerobic digestion or incineration. The calculations concerning an actual WWTP in China (COD = 400 mg/L) demonstrate that AD associated with combined heat and power (CHP) is only capable of generating $0.20\ kW \cdot h/m^3$, which could only supply 53.2% of the actual energy consumption of $0.37\ kW \cdot h/m^3$ (Hao et al., 2018). Although there are some wastewater treatment plants that have attained carbon-neutral operation, they did so with use of co-digestion with organic waste (Wett et al., 2007; SRWTF , 2012; Reardon, 2014). In this assessment, thermal energy recovery can not only offset the energy deficit of direct sludge incineration but also realized energy neutral or even environmental net-zero impact of WWTP. Overall, energy recovery (thermal energy + chemical energy) can attain more than half of the increased benefit.

Furthermore, water reuse (the third largest contributor to the increased benefit, at 16–18%), provided slightly less than half of the thermal energy benefit. It is worth mentioning that phosphorus recovery contributes more than incineration ash reuse, which also proves the importance of phosphorus recovery in wastewater treatment. In short, Fig. 5 indicates that if no thermal energy recovery is associated with the resource/energy recovery, it would be difficult for the resource recovery scenario to attain the net-zero impact on the total environment. In practice, thermal energy recovery is rarely applied in WWTPs. The scientific literature would seem to indicate anaerobic digestion as the preferred option for energy neutrality. It is clear that an integral evaluation of options more objectively presents the way forward and calls for more attention for energy recovery and use from effluent heat.

4. Conclusions

A full-scale WWTP and a scheme with added energy/resource recovery options were quantitatively assessed by an adapted LCA model for its impacts on the total environment. The main conclusions are:

- Resource/energy recovery could help WWTPs approach a net-zero impact, and even benefit the total environment.
- The resource recovery-based assessment revealed that common water reuse through effluent recycling is insufficient to reach a net-zero impact of the WWTPs on the total environment.
- Energy recovery can contribute significantly to benefiting the total environment (71%). In this area, thermal energy recovery plays a significant role (contributing about 40%) in improving the total impact.
- Phosphorus recovery makes limited contributions (6–8%), although more than incineration ash reuse for construction materials does (5%) in improving the environmental impact. Nevertheless, since phosphate is a truly limiting resource, recovery is needed for other reasons.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interest.

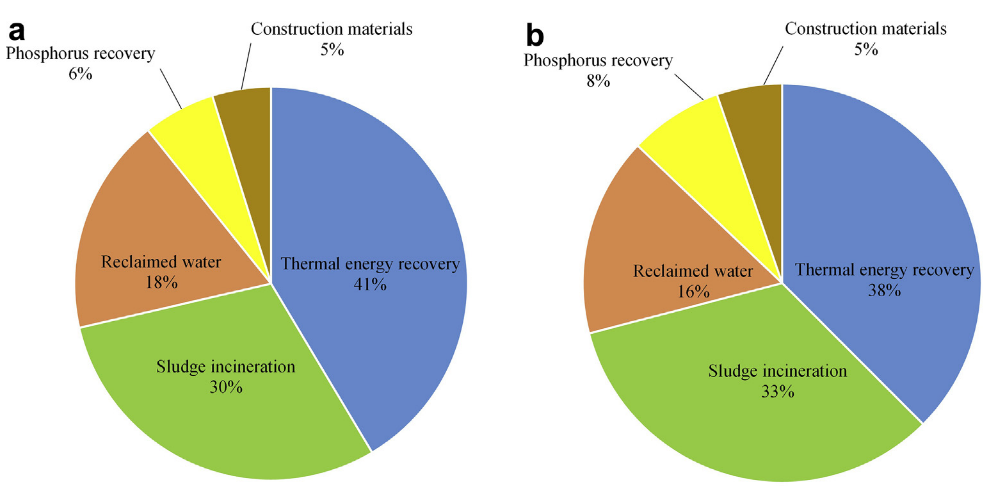

Fig. 5. Contribution of resource recovery processes to the increased benefit on the total environment.

Acknowledgments

The study was financially supported by the National Natural Science Foundation of China (51878022) and also by the special fund from Beijing Advanced Innovation Center of Future Urban Design (2019).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.watres.2019.05.068.

References

Alyaseri, I., Zhou, J., 2017. Towards better environmental performance of wastewater sludge treatment using endpoint approach in LCA methodology. Heliyon 3 (3), e00268. https://doi.org/10.1016/j.heliyon.2017.e00268.

Amann, A., Zoboli, O., Krampe, J., Rechberger, H., Zessner, M., Egle, L., 2018. Environmental impacts of phosphorus recovery from municipal wastewater. Resour. Conserv. Recycl. 130, 127–139. https://dx.doi.org/10.1016/j.resconrec.2017.11.002.

BP Group, 2013. 2012 BP World Energy Statistics Yearbook. https://www.bp.com/content/dam/bp-country/zh_cn/Download_PDF/Report_Stats%20Review/CN-statistical_review_of_world_energy_2013.pdf. Accessed June 2013.

Buonocore, E., Mellino, S., De Angelis, G., Liu, G., Ulgiati, S., 2016. Life cycle assessment indicators of urban wastewater and sewage sludge treatment. Ecol. Indicat. 94, 13–23. https://doi.org/10.1016/j.ecolind.2016.04.047.

Chen, Y., Zheng, H., Yang, F., Zhang, S., 2003. Preliminary study on life cycle assessment method of urban sewage treatment plant and its application case. J. Dalian Univ. Technolgy 43 (3), 292–297. https://doi.org/10.3321/j.issn:1000-8608.2003.03.009 (in Chinese).

Chen, S., Harb, M., Sinha, P., Smith, A.L., 2018. Emerging investigators series: revisiting greenhouse gas mitigation from conventional activated sludge and anaerobic-based wastewater treatment systems. Environ. Sci.: Water Res. Technol. 4, 1739–1758. https://doi.org/10.1039/c8ew00545a.

Corominas, L., Foley, J., Guest, J.S., Hospido, A., Larsen, H.F., Morera, S., Shaw, A., 2013. Life cycle assessment applied to wastewater treatment: state of the art. Water Res. 47, 5480–5492. https://doi.org/10.1016/j.watres.2013.06.049.

Delft, Eneco, 2010. The New Local District Heating Company. http://www.energie-cites.eu/db/delft_582_en.pdf. (Accessed 19 April 2015).

Deng, N., Wang, X., 2003. Life Cycle Assessment. Chemical Industry Press of China, Beijing, China (in Chinese).

Dreyer, L.C., Niemann, A.L., Hauschild, M.Z., 2008. Comparison of three different LCIA methods: EDIP97, CML2001 and Eco-indicator 99. Does it matter which one you choose. Int. J. Life Cycle Assess. 8 (4), 191–200. https://doi.org/10.1007/bf02978471.

Egle, L., Rechberger, H., Zessner, M., 2015. Overview and description of technologies for recovering phosphorus from municipal wastewater. Resour. Conserv. Recycl. 105 (Part B), 325–346. https://doi.org/10.1016/j.resconrec.2015.09.016.

EIA, 2010. Energy & Water Nexus: Availability & Impacts. https://www.eia.gov/conference/2010/session10/chaudhry.pdf.

European Commission - Joint Research Centree - Institute for Environment and Sustainability (EC-JRC), 2010. International Reference Life Cycle Data System (ILCD) Handbook - General Guide for Life Cycle Assessment - Detailed Guidance. March 2010. EUR 24708 EN, first ed. Publications Office of the European Union, Luxembourg. https://doi.org/10.1007/978-94-007-1899-9_11.

Fang, L.L., Valverde-Pérez, B., Damgaard, A., Plósz, B.G., Rygaard, M., 2016. Life cycle assessment as development and decision support tool for wastewater resource recovery technology. Water Res. 88, 538–549. https://doi.org/10.1016/j.watres.2015.10.016.

Foley, J., de Haas, D., Hartley, K., Lant, P., 2010. Comprehensive life cycle inventories of alternative wastewater treatment systems. Water Res. 44 (5), 1654–1666. https://doi.org/10.1016/j.watres.2009.11.031.

Gallego-Schmid, A.G., Tarpani, R.R.Z., 2019. Life cycle assessment of wastewater treatment in developing countries: a review. Water Res. 153, 63–79. https://doi.org/10.1016/j.watres.2019.01.010.

Gao, H., Scherson, Y.D., Wells, G.F., 2014. Towards energy neutral wastewater treatment: methodology and state of the art. Environ. Sci.: Processes Impacts 16 (6), 1223–1246. https://doi.org/10.1039/c4em00069b.

Gao, C., Chen, S., Chen, S., 2016. Life cycle assessment of integrated iron and steel works in China. J. Harbin Inst. Technol. 48 (4), 177–181. https://doi.org/10.11918/j.issn.0367-6234.2016.04.030 (in Chinese).

GB 18918-2002, 2002. Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant. Standards Press of China, Beijing (in Chinese).

GB 50014-2006, 2016. Code for Design of Outdoor Wastewater Engineering. Standards Press of China, Beijing (in Chinese).

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., van Zelm, R., 2009. ReCiPe 2008. A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level, p. 1.

Guest, J.S., Skerlos, S.J., Barnard, J.L., Beck, M.B., Daigger, G.T., Hilger, H., et al., 2009. A new planning and design paradigm to achieve sustainable resource recovery from wastewater. Environ. Sci. Technol. 43 (16), 6126–6130. https://doi.org/10.1021/es9010515.

Hao, X., 2006. Sustainable Treatment Technologies of Wastewater-Wastes. China Archit. Build. Press (in Chinese).

Hao, X., Liu, R., Huang, X., 2015. Evaluation of the potential for operating carbon neutral WWTPs in China. Water Res. 87, 424–431. https://doi.org/10.1016/j.watres.2015.05.050.

Hao, X., Fang, X., Li, J., Jiang, H., 2018. Analysis of potential in carbon-neutral operation of WWTPs. China Water & Wastewater 34 (10), 11–16 (in Chinese).

Hao, X., Chen, Q., Li, J., Jiang, H., Liang, Y., 2019. The ultimate approach to handle excess sludge: incineration and drying. China Water & Wastewater 35 (2) (in Chinese).

Heidrich, E.S., Curtis, T.P., Dolfing, J., 2011. Determination of the internal chemical energy of wastewater. Environ. Sci. Technol. 45 (2), 827–832. https://doi.org/10.1021/es103058w.

Hellweg, S., Milà i Canals, L., 2014. Emerging approaches, challenges and opportunities in life cycle assessment. Science 344 (6188), 1109–1113. https://doi.org/10.1126/science.1248361.

Hospido, A., Moreira, M.T., Fernández-Couto, M., Feijoo, G., 2004. Environmental performance of a municipal wastewater treatment plant. Int. J. Life Cycle Assess. 9 (4), 261–271. https://doi.org/10.1007/bf02978602.

Huang, X., Luo, X., Li, Z., Wang, D., 2014. Life cycle assessment of a wastewater treatment plant and comparison analysis. Water Resour. Prot. 30 (1), 90–94. https://doi.org/10.3969/j.issn.1004-6933.2014.01.018 (in Chinese).

Huppes, G., van Oers, L., 2010. Recommended Weighting Method for Measuring the EU-27 Overall Environmental Impact. CML, Leiden.

IKE, 2010. Chinese Life Cycle Database – CLCD. http://www.ike-global.com/products-2/chinese-lca-database-clcd.

International Standards Organisation (ISO), 2006a. ISO 14040: 2006 Environmental Management - Life Cycle Assessment - Principles and Framework. https://doi.org/10.3403/01139131.

International Standards Organisation (ISO), 2006b. ISO 14044: 2006 Environmental Management - Life Cycle Assessment - Requirements and Guidelines. https://doi.org/10.3403/01139131.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. IGES, Japan. https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.

Jossa, P., Remy, C., 2015. Life Cycle Assessment of Selected Processes for P Recovery from Sewage Sludge, Sludge Liquor or Ash. P-Rex project, p. 86.

Kampschreur, M.J., Temmink, H., Kleerebezem, R., Jetten, M.S.M., van Loosdrecht, M.C.M., 2009. Nitrous oxide emission during wastewater treatment. Water Res. 43 (17), 4093–4103. https://doi.org/10.1016/j.watres.2009.03.001.

Kollmann, R., Neugebauer, G., Kretschmer, F., Truger, B., Kindermann, H., Stoeglehner, G., Ertl, T., Narodoslawsky, M., 2016. Renewable energy from wastewater - practical aspects of integrating a wastewater treatment plant into local energy supply concepts. J. Clean. Prod. 155 (2017), 119–129. https://doi.org/10.1016/j.jclepro.2016.08.168.

Liang, S., 2012. Research on the Environmental Impact Load of the Urban Wastewater Treatment Plant by the Method of Life Cycle Assessment. Diss. Harbin Institute of Technology, Harbin, China (in Chinese).

Liu, Z., 2010. Life cycle analysis in environmental impact assessment. China resour. Compr. Util. 28 (3), 54–57. https://doi.org/10.3969/j.issn.1008-9500.2010.03.021 (in Chinese).

Loubet, P., Roux, P., Loiseau, E., Bellon-Maurel, V., 2014. Life cycle assessments of urban water systems: a comparative analysis of selected peer-reviewed literature. Water Res. 67, 187–202. https://doi.org/10.1016/j.watres.2014.08.048.

Lundin, M., Bengtsson, M., Molander, S., 2000. Life cycle assessment of wastewater systems: influence of system boundaries and scale on calculated environmental loads. Environ. Sci. Technol. 34 (1), 180–186. https://doi.org/10.1021/es990003f.

Lundin, M., Olofsson, M., Pettersson, G.J., Zetterlund, J., 2004. Environmental and economic assessment of sewage sludge handling options. Resour. Conserv. Recycl. 41 (4), 255–278. https://doi.org/10.1016/j.resconrec.2003.10.006.

Luo, X., Huang, X., Wang, D., Li, Z., 2013. The theory of life cycle assessment and its application in wastewater treatment. Environ. Eng. 31 (4), 118–122. https://doi.org/10.7617/j.issn.1000-8942.2013.04.030 (in Chinese).

Lynn, C.J., Dhir, R.K., Ghataora, G.S., 2018. Environmental impacts of sewage sludge ash in construction: leaching assessment. Resour. Conserv. Recycl. 136, 306–314. https://doi.org/10.1016/j.resconrec.2018.04.029.

McQuay, 2018. Technical Manual of Water Source Heat Pump. http://www.mcquay.com.cn/list_76.aspx?lcid=13.

Ministry of Ecology and Environment, 2018. Annual Statistic Report on Environment in China 2018. Environment Press of China, Beijing (in Chinese). http://www.zhb.gov.cn/gzfw_13107/hjtj/hjtjnb.

Mo, W., Zhang, Q., 2012. Can municipal wastewater treatment systems be carbon neutral? J. Environ. Manag. 112, 360–367. https://doi.org/10.1016/j.jenvman.2012.08.014.

Mo, W., Zhang, Q., 2013. Energy-nutrients-water nexus: integrated resource recovery in municipal wastewater treatment plants. J. Environ. Manag. 127, 255–267. https://doi.org/10.1016/j.jenvman.2013.05.007.

Monteith, H.D., Sahely, H.R., Maclean, H.L., Bagley, D.M., 2005. A rational procedure for estimation of greenhouse-gas emissions from municipal wastewater treatment plants. Water Environ. Res. 77 (4), 390–403. https://doi.org/10.2175/106143005X51978.

National Bureau of Statistics, 2018. China Statistical Yearbook on Environment 2018. Statistics Press of China, Beijing (in Chinese). http://www.stats.gov.cn/tjsj/ndsj/

2013/indexch.htm.
Niemela, M., Saarela, R., 2009. The Wastewater Utilization in Kakola Heat Pump Plant. http://www.districtenergyaward.org/wp-content/uploads/2012/e10/New_scheme_Finland_Turku.pdf.
Nowak, O., Enderle, P., Varbanov, P., 2015. Ways to optimize the energy balance of municipal wastewater systems: lessons learned from austrian applications. J. Clean. Prod. 88, 125–131. https://doi.org/10.1016/j.jclepro.2014.08.068.
Pasqualino, J.C., Meneses, M., Abella, M., Castells, F., 2009. LCA as a decision support tool for the environmental improvement of the operation of a municipal wastewater treatment plant. Environ. Sci. Technol. 43 (9), 3300–3307. https://doi.org/10.1021/es802056r.
Pasqualino, J.C., Meneses, M., Castells, F., 2010. Life cycle assessment of urban wastewater reclamation and reuse alternatives. J. Industrial Ecol. 15 (1), 49–63. https://doi.org/10.1111/j.1530-9290.2010.00293.x.
Pennington, D.W., Potting, J., Finnveden, G., Lindeijer, E., 2004. Life cycle assessment Part 2: current impact assessment practice. Environ. Int. 30 (5), 721–739. https://doi.org/10.1016/j.envint.2003.12.009.
Peters, G., Andrew, R., Korsbakken, J.I., 2015. World social science report. Global Carbon Project 531–532. http://www.globalcarbonproject.org/nitrousoxidebudget/index.htm.
Reardon, R., 2014. Separate or combined sidestream treatment: that is the question. Fla. Water Resour. J 52–58.
Remy, C., Boulestreau, M., Warneke, J., Jossa, P., Kabbe, C., Lesjean, B., 2016. Evaluating new processes and concepts for energy and resource recovery from municipal wastewater with life cycle assessment. Water Sci. Technol. 73 (5), 1074–1080. https://doi.org/10.2166/wst.2015.569.
Roeleveld, P.J., Klapwijk, A., Eggels, P.G., Rulkens, W.H., Starkenburg, W.V., 1997. Sustainability of municipal waste water treatment. Water Sci. Technol. 35 (10), 221–228. https://doi.org/10.1016/s0273-1223(97)00199-6.
Shiu, H.Y., Lee, M., Chiueh, P.T., 2017. Water reclamation and sludge recycling scenarios for sustainable resource management in a wastewater treatment plant in kinmen islands, taiwan. J. Clean. Prod. 152, 369–378.
Shizas, I., Bagley, D.M., 2004. Experimental determination of energy content of unknown organics in municipal wastewater streams. J. Energy Eng. 130 (2), 45–53. https://doi.org/10.1061/(asce)0733-9402(2004)130:2(45).
SRWTF (Sheboygan Regional Wastewater Treatment Facility), 2012. Treatment Plant Brochure accessed 15.01.15. http://www.sheboyganwwtp.com/files/2012/pdf/Treatment%20Plant%20Brochure%202012.pdf.
Świerczek, L., Cieślik, B.M., Konieczka, P., 2018. The potential of raw sewage sludge in construction industry – a review. J. Clean. Prod. 200, 342–356. https://doi.org/10.1016/j.jclepro.2018.07.188.
Teodosiu, C., Barjoveanu, G., Sluser, B.R., Popa, S.A.E., Trofin, O., 2016. Environmental assessment of municipal wastewater discharges: a comparative study of evaluation methods. Int. J. Life Cycle Assess. 21 (3), 395–411. https://doi.org/10.1007/s11367-016-1029-5.
Tomei, M.C., Bertanza, G., Canato, M., Heimersson, S., Laera, G., Svanström, M., 2015. Techno-economic and environmental assessment of upgrading alternatives for sludge stabilization in municipal wastewater treatment plants. J. Clean. Prod. 112, 3106–3115. https://doi.org/10.1016/j.jclepro.2015.10.017.
Vera, L., Sun, W., Iftikhar, M., Liu, J., 2015. LCA based comparative study of a microbial oil production starch wastewater treatment plant and its improvements with the combination of CHP system in Shandong, China. Resour. Conserv. Recycl. 96, 1–10. https://doi.org/10.1016/j.resconrec.2014.09.013.
Vlasopoulos, N., Memon, F.A., Butler, D., Murphy, R., 2006. Life cycle assessment of wastewater treatment technologies treating petroleum process waters. Sci. Total Environ. 367 (1), 58–70. https://doi.org/10.1016/j.scitotenv.2006.03.007.
Wang, X., Mccarty, P.L., Liu, J., Ren, N., Lee, D., Yu, H., Qian, Y., Qu, J., 2015a. Probabilistic evaluation of integrating resource recovery into wastewater treatment to improve environmental sustainability. Proc. Natl. Acad. Sci. Unit. States Am. 112 (5), 1630–1635. http://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1410715112/-/DCSupplemental.
Wang, X., Wang, X., Huppes, G., Heijungs, R., Ren, N., 2015b. Environmental implications of increasingly stringent sewage discharge standards in municipal wastewater treatment plants: case study of a cool area of China. J. Clean. Prod. 94, 278–283. https://doi.org/10.1016/j.jclepro.2015.02.007.
Wett, B., Buchauer, K., Fimml, C., 2007. Energy self-sufficiency as a feasible concept for wastewater treatment systems. In: Proc. IWA Leading Edge Technology Conference, Singapore, Asian Water, Sept. 21–24.
Xu, C., 2015. Life Cycle Environmental and Economic Assessment of Sewage Sludge Treatment in China. Diss. Shandong University, Shandong, China (in Chinese).
Yang, S., 2013. The Method and Model Research of GHG Accounting of Urban Sewage Treatment System. Diss. Chongqing University, Chongqing, China (in Chinese).
Zhao, X., Yang, J., Ma, F., 2018. Set organic pollution as an impact category to achieve more comprehensive evaluation of life cycle assessment in wastewater-related issues. Environ. Sci. Pollut. Res. 25 (6), 5960–5968. https://doi.org/10.1007/s11356-017-0895-0.
Zhu, L., Liu, B., Wang, F., Bi, J., 2013. Raising discharge standards leads to environmental problem shifting in China. Water Sci. Technol. 68 (12), 2605–2612. https://doi.org/10.2166/wst.2013.537.