Title

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Journal

Environmental science and pollution research international, 28(26)

ISSN

0944-1344

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Publication Date

2021-07-01

DOI

10.1007/s11356-021-13004-7

Peer reviewed

Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-021-13004-7

RESEARCH ARTICLE

Environmental tradeoffs in municipal wastewater treatment plant upgrade: a life cycle perspective

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Received: 23 September 2020 / Accepted: 12 February 2021

Abstract
Municipal wastewater treatment plants (WWTPs) play an indispensable role in improving environmental water quality in urban areas. Existing WWTPs, however, are an important source of greenhouse gas (GHG) emissions and may not be able to treat increasingly complicated wastewater or meet stringent environmental standards. These WWTPs can be updated to address these challenges, and different technologies are available but with potentially different environmental implications. Life cycle assessment (LCA) is a widely used approach to identify alternatives with lower environmental footprint. In this study, LCA was applied to an actual urban WWTP, considering four scenarios involving upgrading and energy-resource recovery. The environmental performance with respect to life cycle GHG emissions and eutrophication impact was analyzed. The environmental benefits of reduced water pollution and energy and material displacement associated with energy-resource recovery process were also considered. The results showed tradeoffs among the four scenarios. Although upgrading the studied WWTP would meet discharge standard for total phosphorus and reduce total eutrophication impact by about 19%, it would increase GHG emissions by at least 16%. Besides, the energy-resource recovery mode for existing WWTP (S2) performs the best in terms of GHG emissions. For different biogas utilization methods, combined heat and power (CHP) system is superior to the existing method of delivering biogas to gas grid, in terms of energy recovery or reduction of GHG emissions and eutrophication impact. Our research results may provide a reference for plant managers to select the most environmentally friendly upgrade scheme and energy-resource recovery technique for future upgrade projects.

Keywords Environmental tradeoffs · Life cycle assessment · Wastewater treatment upgrade · Energy-resource recovery · GHG emissions · Eutrophication impact

Responsible Editor: Philippe Loubet

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Introduction

Municipal wastewater treatment plants (WWTPs) are an indispensable component of urban systems for removing harmful substances in wastewater before discharging it into the environment. Although WWTPs can reduce the environmental impact of water pollution, they release potent greenhouse gases (GHG), CH_4 and N_2O, during the treatment process and consume a large amount of energy and materials, which cause GHG emissions elsewhere. Globally, WWTPs are responsible for an estimated 3% of total GHG emissions (Magill 2016).

In China, the total municipal wastewater treatment capacity reached 51.9 billion m^3 (or 167 million m^3/day) in 2018, removing ~ 1.2 and ~ 12.4 million metric tons of ammonia nitrogen (NH_3-N) and chemical oxygen demand (COD), respectively (MEE 2019). Continuous urbanization and industrialization present growing challenges to WWTPs in China. The amount of wastewater treated increases annually,

Published online: 04 March 2021

impurities contained in wastewater are becoming more complicated (Tang et al. 2016), and more stringent discharge standards are being implemented to address emerging contaminants (Gao 2018).

Existing WWTPs in China address these challenges through upgrading their treatment process technologies (Hao et al. 2018). For example, a WWTP can invest in more effective denitrification and dephosphorization technologies or more energy-efficient equipment to meet higher wastewater discharge standards and reduce operating costs. It can also invest in energy-resource recovery technologies to recycle potential energy and substances (organic matter, nutrients, etc.) from wastewater and sludge, which would have been otherwise wasted. Previous studies have reported various methods by which WWTPs and sludge treatment plants (STPs) achieve energy-resource recovery, including reuse of treated water (Pedrero et al. 2010) and recovery of nutrient elements by ammonia stripping (Boehler et al. 2012) and struvite precipitation (Rahman et al. 2014). Another method is to supply biogas from anaerobic digestion to a combined heat and power (CHP) system for energy recovery (Vera et al. 2015; Bertanza et al. 2018).

Although upgrading existing WWTPs can improve effluent quality and resource recycling potential of existing WWTPs, it may also increase energy and material demand and lead to additional GHG and other emissions (Bertanza et al. 2018). It is, therefore, important to gain a better understand of the environmental costs and benefits associated with WWTP upgrading, to support informed decision-making and identify potential improvement opportunities.

Life cycle assessment (LCA) is a widely used approach that evaluates both the direct and indirect environmental impacts associated with a product, a service, or a technology (Yang 2016). And it has been increasingly applied to wastewater treatment industry. Comprehensive reviews of wastewater treatment LCAs have been done by Corominas et al. (2013, 2020), Loubet et al. (2014), Zang et al. (2015), and Gallego-Schmid and Tarpani (2019). LCA studies on wastewater treatment can be divided into three categories with different research objectives: (1) evaluating a single emerging treatment technology or system (e.g., Lutterbeck et al. 2017; Martinez et al. 2019); (2) comparing different wastewater treatment processes, options, or systems (e.g., Hengen et al. 2014; Limphitakphong et al. 2016; Malila et al. 2019); and (3) analyzing the integration or combination of wastewater treatment processes and other techniques (e.g., microalgal biomass production of Diniz et al. 2017; different biogas technologies of Nasution et al. 2018; solar-assisted heat pump of Munoz et al. 2019). Many LCA studies have examined the energy consumption (Zhang et al. 2010; Piao et al. 2016), GHG emissions (e.g., Rodriguez-Garcia et al. 2012; Polruang et al. 2018; Song et al. 2019), and energy recovery potential of WWTPs (e.g., Wang et al. 2016; Hao et al. 2019), but few have investigated the environmental tradeoffs in WWTPs from the perspective of different upgrade options, especially studying the process changing from constant water level sequencing batch reactor (CWSBR) to biological combined system (BIOCOS) from a sustainability or LCA perspective and comparing different biogas utilization methods of exporting to gas grid and CHP system.

In this study, LCA was applied to a WWTP in northeast China. Currently, some of the plant's treated effluent quality indicators exceed the water quality standards. Therefore, an upgrade project has been embarked on, with a number of upgrading scenarios proposed. The environmental performance with respect to energy use, material use, water use, life cycle GHG emissions, and eutrophication impact was analyzed, and those aspects of existing technologies for comparison were also studied. For different upgrade techniques in WWTPs, it is unclear what their own environmental impacts would be because they would also require additional material and energy inputs. The question of environmental burden shifting is particularly interesting (Yang et al. 2012); i.e., the upgrade techniques will improve the existing treatment capacity and yield cleaner wastewater but, in the meantime, could make other environmental problems worse via the material and energy consumption. To answer these questions requires quantifying the life cycle environmental impacts of WWTP upgrade techniques. On the practical side, our results may be used as a reference for plant managers to select the most environmentally friendly upgrade scheme. And the life cycle framework developed for this WWTP may also help analyze the environmental benefits of energy-resource recovery techniques for future wastewater treatment upgrade projects.

Methods

Goal and scope definition

Plant information and LCA goal and scope definition

The studied WWTP (A) is located in Liaoning in northeast China. The designed treatment capacity of WWTP A is 30,000 m^3/day, and its secondary treatment employs the process of CWSBR, designed to reach the 1-A discharge quality standard of the Chinese "Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant" (GB18918-2002) (MEE 2003).

Our LCA study aims at comparing the differences of energy use, material use, water use, life cycle GHG emissions, and eutrophication impact for, in total, four wastewater treatment scenarios, including a baseline scenario reflecting the status quo. Results are measured in MJ, kg, kg, kg CO_2 eq, and kg Phosphate eq, respectively. The functional unit of the LCA is set as treating 1 m^3 of wastewater.

The scope of study includes all the operational stages of WWTP and STP, and relevant auxiliary processes such as the production of electric power, chemicals, and tap water. Environmental impacts of chemical transport and plant construction and demolition are not considered in this LCA study. Details of the four scenarios are described as follows.

Scenarios description

Scenario 1 (S1) Existing-WWTP + STP. S1 considers existing technologies employed in WWTP A. The output sludge from WWTP A is directly transported to a nearby STP A through a sludge pump and a pipeline. STP A applies the process of sludge anaerobic digestion combined with industrial biological biogas production. Compared with other WWTPs in the city, the WWTP A does not need to transport sludge via vehicles. In STP A, biogas is produced through an anaerobic digestion process, and biogas slurry is treated through the simultaneous nitrification, anaerobic ammonia oxidation, and denitrification process to eliminate nitrogen and recover phosphate. In biogas treatment stage, some of the desulfurized biogas is burned and reused by a biogas boiler, with the remainder compressed and delivered to the city's gas grid as a supplemental gas source. After a year-round monitoring, the actual daily average wastewater treatment flow rate of WWTP A is 22,000 m^3/day, and the sludge yield is 0.398 kg/m^3.

Scenario 2 (S2) Energy-Resource Recovery for Existing-WWTP. S2 is a simulated energy-resource recovery scenario, integrating the relatively mature techniques of anaerobic digestion (for biogas production), digestion liquid treatment, and biogas slurry treatment (for phosphate recovery) from STP A with the wastewater treatment processes from WWTP A. In addition, to treat the biogas generated from anaerobic digestion, a CHP system is considered, which generates electricity and heat to offset some of the energy needed during WWTP operation. It should be noted that the sludge disposal stage of S2 consumes less electricity than that of S1, as S2 does not require a pump and pipeline to transport sludge, which is one of the features of this energy-resource recovery mode.

Scenario 3 (S3) Upgrade-WWTP + STP. S3 considers an upgrade of WWTP A. In recent years, some of the effluent water quality parameters exceeded national standards due to a deterioration of the influent quality. Therefore, it is necessary to partially reconstruct and upgrade WWTP A to meet the water quality requirements. The upgrade project is based on the principle of minimizing disruption to the existing plant: to the extent possible, new designs are additive to existing conditions and carried out on the same locations. The main improvements include (1) changing the secondary treatment process from CWSBR to BIOCOS to improve denitrification efficiency and (2) adding an advanced tertiary treatment stage to improve dephosphorization. The designed treatment capacity of upgrade-WWTP is 30,000 m^3/day, and designed sludge yield is 0.434 kg/m^3. The output sludge from the upgraded WWTP will also be transported to STP A through a sludge pump and pipeline. The sludge treatment process of S3 is the same as S1.

Scenario 4 (S4) Energy-Resource Recovery for Upgrade-WWTP. S4 is also a simulated energy-resource recovery scenario, combining the stages of sludge disposal and energy-resource recovery (anaerobic digestion, digestion liquid treatment and biogas slurry treatment, and the CHP system) from S2 with the upgrading wastewater treatment stages (primary treatment, secondary treatment, and tertiary treatment) from S3. Besides, there is no need to have a pump and pipeline to transport sludge in S4.

The influent-effluent quality indicator details of the four scenarios are shown in Table 1. It is worth noting that the designed standards for S3 and S4 are targets that are being proposed, simulated data of S3 and S4 are calculated based on actual data of S1 and S2, and effluent total phosphorus (TP) is designed at 0.5 mg/L after upgrade. Thus, while the design standards are the nominal goal, simulated data for S3 and S4 was used, based on the real, measured results from S1 and S2. The results based on the designed standards are not reported, since in general the water quality of the effluent would be worse than what is actually achieved by the upgraded plant.

Figure 1 depicts the process flow of the four scenarios, including all relevant operational units of the study scope, from wastewater input to different methods of utilizing biogas output from sludge treatment.

Inventory analysis

Life cycle inventories of the four scenarios are established based on actual monitoring operation data (wastewater treatment stages of S1 and S2), upgrade project report (wastewater treatment stages of S3 and S4), and reference data from relevant studies, as shown in *Table S1*. In this work, Gabi 8.5 (Thinkstep 2018) and eBalance (IKE 2010a) are both applied for the LCA analysis. Specifically, Gabi is mainly used for calculation and eBalance used to provide additional data. The upstream background data on electricity, chemicals, tap water, and the other supplementary products are from databases of the two software programs. Because Gabi does not have data for the intermediate product of "biogas slurry", digestion liquid treatment and biogas slurry treatment were merged into one stage during the assessment process, and denoted it as "DLBS". Life cycle inventory data for $FeSO_4$, PAM (polyacrylamide), MgO, and $FeCl_3$ production is extracted from the CLCD-China-ECER database of eBalance (IKE 2010b) and inserted into Gabi. The electrical, thermal, and total

Table 1 Influent-effluent quality indicators of the four scenarios (mg/L)

Item	Influent quality indicators				Effluent quality indicators			
	China 1-A standards	Actual data of S1 and S2	Design standards for S3 and S4	Simulated data of S3 and S4	China 1-A standards	Actual data of S1 and S2	Design standards for S3 and S4	Simulated data of S3 and S4
COD	400	520.01	500	520.01	50	20.16	50	20.16
BOD_5	200	183.15	200	183.15	10	3.52	10	3.52
SS	220	273.78	350	273.78	10	5.05	10	5.05
TN	48	52.67	70	52.67	15	8.87	15	8.87
NH_3-N	30	25.18	45	25.18	5	0.85	5	0.85
TP	3	7.42	8	7.42	0.5	1.11	0.5	0.5

COD chemical oxygen demand, *BOD_5* biochemical oxygen demand, *SS* suspended solids, *TN* total nitrogen, *NH_3-N* ammonia nitrogen, *TP* total phosphorus

efficiencies of the CHP system in S2 and S4 are set as 40%, 50%, and 90%, respectively (Yan et al. 2017).

Impact assessment

For impact assessment, the widely used midpoint CML method (Guinee et al. 2002) was applied. In this step, the environmental impacts of different pollutants are aggregated to a total score for a given impact category based on their characterization factors. This study focuses on global warming and eutrophication impact, which are the most commonly studied impact categories in WWTP-LCA studies (Gallego-Schmid and Tarpani 2019; Lamnatou et al. 2019).

In addition, the environmental impacts from reduced concentrations of water pollutants in the effluent (Godin et al. 2012) and from avoided energy use associated with the energy-resource recovery process during wastewater treatment (Niero et al. 2014) were considered. The negative eutrophication impact in this study is similar to GHG savings, which are often treated as negative GHG emissions (Tilman et al. 2006; Gelfand et al. 2013; Yang et al. 2018). Considering WWTP as providing wastewater treatment service, its net environmental benefit (NEB) was calculated to describe the eutrophication reduction caused only by removing water pollutants (Godin et al. 2012; Lorenzo-Toja et al. 2016). Specifically, the PT and ST stages of S1 and S2 and the PT, ST, and TT stages of S3 and S4 reduce water pollutants and corresponding environmental impacts. In the BT stage of S1 and S3, a fraction of the biogas is burned through a biogas boiler to provide heat, while the remaining biogas is delivered to gas grid, displacing equivalent amounts of coal gas and its environmental impacts. In the BT stage of S2 and S4, electricity and heat are recovered through the CHP system, similarly displacing equivalent amounts of electricity and heat and their environmental impacts. Furthermore, the DLBS stage of all four scenarios offsets phosphate outside the plant and reduces the environmental impacts along its life cycle.

Results

Life cycle GHG emissions and contributing sources

Figure 2 shows that upgrading WWTP in our study would lead to increased GHG emissions (net), with S3 (1.67 kg CO_2 eq)>S4 (1.55 kg CO_2 eq)>S1 (1.33 kg CO_2 eq)>S2 (1.21 kg CO_2 eq). It should be pointed out that GHGs covered in our study are CO_2, CH_4, and N_2O through results traced in the software and inventory analysis. In terms of direct emissions and process inputs (energy, materials, and water), direct GHG emissions account for the largest proportion, followed by GHG emissions embedded in energy use and then in material use.

In all four scenarios, GHG emissions are dominated by the ST stage, followed by the SD stage (Fig. 3a). The increased GHG emissions from ST and TT stages are the main reason why upgrade would lead to greater GHG emissions. The SD stage in S3 and S1 consumes more electricity due to sludge pump and transport, which is the main source of the greater GHG emissions of the WWTP+STP mode. For the PT, ST, and TT stages, the main source of CO_2, CH_4 and N_2O is the treatment of BOD_5, COD, and TN. Since the upgrade for the existing WWTP in our analysis is mainly aimed at the standard exceeding of TP, with little influence on BOD_5, COD, and TN, the emissions and types of GHG from the wastewater treatment stages in the four scenarios (including the same emissions of CH_4 and N_2O from SD stage) are the same. Besides, direct GHG emissions from other stages are relatively small, so GHG emissions do not differ greatly across the four scenarios.

For the two existing WWTP scenarios (S1 and S2), the influence on GHG emissions of energy use is significantly higher than that of material use. But for S3 and S4, the contribution of energy use to GHG emissions is only slightly higher than that of material use, which is mainly due to GHG emissions from $FeCl_3$ at the TT stage and acetic acid and Na_2CO_3 at the ST stage after upgrading. Although water

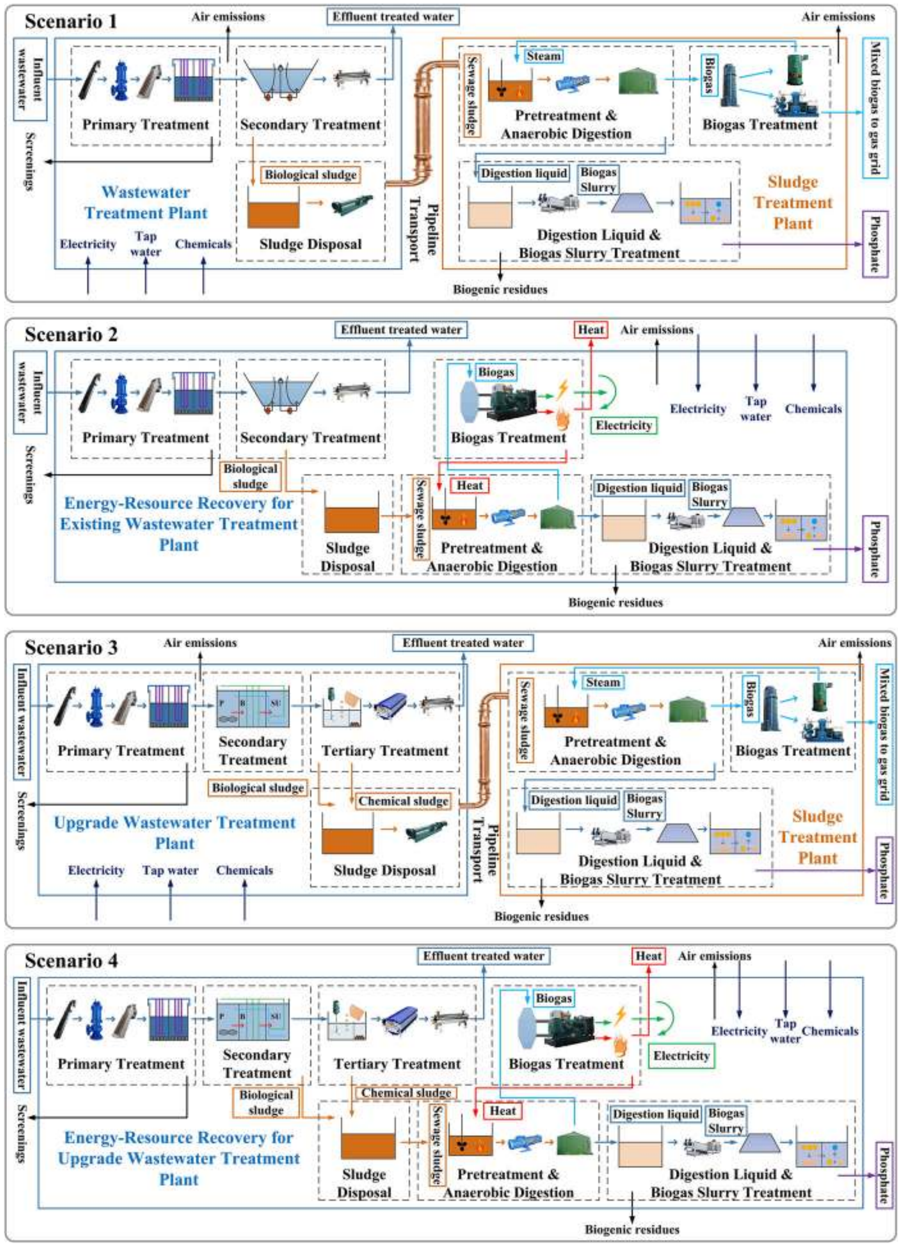

Fig. 1 Process flow of the four scenarios

use cannot be ignored, its influence on GHG emissions is far less than that of the other three factors (Fig. 2). *Figure S1* in the supplementary material shows the contribution of different operational stages in the four factors: in terms of direct GHG emissions, the ST and SD stages contribute the most in all the four scenarios. GHG emissions from energy use are also dominated by the ST stage, the reason to be discussed below. For material use, the DLBS stage in S1 and S2 contributes more than 95% due to the input of MgO, while the use of $FeCl_3$ at the TT stage, of acetic acid, and Na_2CO_3 at the ST, and of MgO at the DLBS, is the main contributor in S3 and S4. For GHG emissions from water use, the PAD stage contributes the most in S1 and S3 while the BT stage contributes the most in S2 and S4. Below, each emission source by stages is described in detail.

Process energy use (electricity) in different scenarios differs, with S3 (1.76 MJ/m^3)>S4 (1.46 MJ/m^3)>S1 (1.35 MJ/m^3)>S2 (1.07 MJ/m^3) (Fig. 3b). Noticeably, energy use in the upgrade wastewater treatment scenarios is relatively larger (S3, S4>S1, S2), and in the energy-resource recovery wastewater treatment scenarios is relatively smaller (S3>S4, S1>S2). Contribution analysis indicates that the ST stage contributes the most to total process energy use in all four scenarios. Energy use from the ST stage in S3 and S4 is higher than in S1 and S2, and that is mainly because the BIOCOS process adopted by the upgrade-WWTP increases electricity consumption, compared with the CWSBR process employed by the ST stage of the existing WWTP. Meanwhile, the TT stage in S3 and S4 also increases electricity use; therefore, the ST and TT stages of S3 and S4 are the main reason why total process energy use in upgrade wastewater treatment scenarios is higher than in the existing wastewater treatment scenarios. Energy use of the SD stage in S4 and S2 is less than that in S3 and S1, mainly because of the reduction in electricity consumption by not transporting sludge to STP via pump and pipeline. In general, the total energy use by wastewater treatment stages (PT+ST+TT+SD) is clearly larger than that by sludge treatment stages (PAD+DLBS+BT).

Material use in our analysis is comprised of different kinds of chemicals used in each operational stage. Figure 3c shows S3 and S4 use a much higher amounts of materials than S1 and S2: S4 (0.287 kg/m^3)≈S3 (0.286 kg/m^3)>S2 (0.024 kg/m^3)≈S1 (0.023 kg/m^3). It is clear that upgrading would substantially increase the material consumption relative to the baseline scenario (S1). Specifically, $FeCl_3$ consumed by the TT stage, acetic acid, and Na_2CO_3 required by the ST stage of S3 and S4 are the main sources that total material use in the upgrade scenarios is greater than in the existing ones (S4, S3>S2, S1). But there is no obvious difference between the energy-resource recovery wastewater treatment mode and corresponding WWTP+STP mode (S4≈S3, S2≈S1) in terms of material use. In total, the wastewater treatment stages (PT+ST+TT+SD) contribute more than 80% of the total material use in S1 and S2 and more than 98% in S3 and S4.

Relative to the baseline, more water would be needed in the upgrade scenarios, with S4 (0.886 kg/m^3)>S2 (0.682 kg/m^3)≈S3 (0.679 kg/m^3)>S1 (0.491 kg/m^3) (Fig. 3d). Moreover, total water use in the energy-resource recovery wastewater treatment mode is higher than in the corresponding WWTP+STP mode (S4>S3, S2>S1). This is mainly because tap water consumed by CHP system applied by the BT stage in the former mode is higher than that in the latter. And tap water required by the TT stage in S4 and S3 is the main source that total water use in upgrade scenarios is greater than that in existing ones (S4>S2, S3>S1). Overall, compared with S1, total water use of the other three scenarios increases by 38.79%, 38.16%, and 80.44%, respectively. The sludge treatment stages (PAD+DLBS+BT) in total contribute more than 95% to total water use in S1 and S2, and 77% and 82% in S3 and S4, respectively.

As shown in Fig. 3b, the total amount of energy recovery (absolute value) across the four scenarios is: S4 (0.428 MJ/m^3)>S3 (0.409 MJ/m^3)>S2 (0.393 MJ/m^3)>S1 (0.375 MJ/m^3). Energy recovery in all scenarios is provided by the BT stage. For S1 and S3, energy recovery is from (1) the saved heat provided by a fraction of biogas to meet the requirement of PAD stage and (2) the reduced coal gas displaced by the remaining biogas delivered to gas grid. For S2 and S4, electricity and heat could be recovered through the CHP system. Due to greater biogas production from increased sewage sludge after upgrading, the energy recovery of upgrade-WWTP scenarios is higher (S4, S3>S2, S1). And the reason why S4>S3 and S2>S1 is that the total energy recovered amount via CHP system is greater than the total heat reduced from biogas (self-used and delivered to gas grid). Notably, from the perspective of energy recovery, the treatment of biogas to recover electricity and heat through the CHP system is more effective.

As Fig. 3c shows, compared with the total material use in S3 and S4, the amount of phosphate recovered in DLBS is very small; therefore, the resource recovery has little influence on net material use for the two upgrade-WWTP scenarios. But for S1 and S2, resource recovery can compensate for over 55% of the total material use.

The GHG reductions in S4 and S2 are significantly higher than that in S3 and S1. Moreover, although the amount of energy recovered in S3 is higher than in S2, the GHG reductions in S2 are larger, which is mainly because GHG reductions from electricity displacement through the CHP system in S2 are higher than that of the biogas utilization mode in S3. Therefore, from the perspective of GHG reductions, the energy-resource recovery mode has better environmental benefits due to the electricity recovery via CHP system.

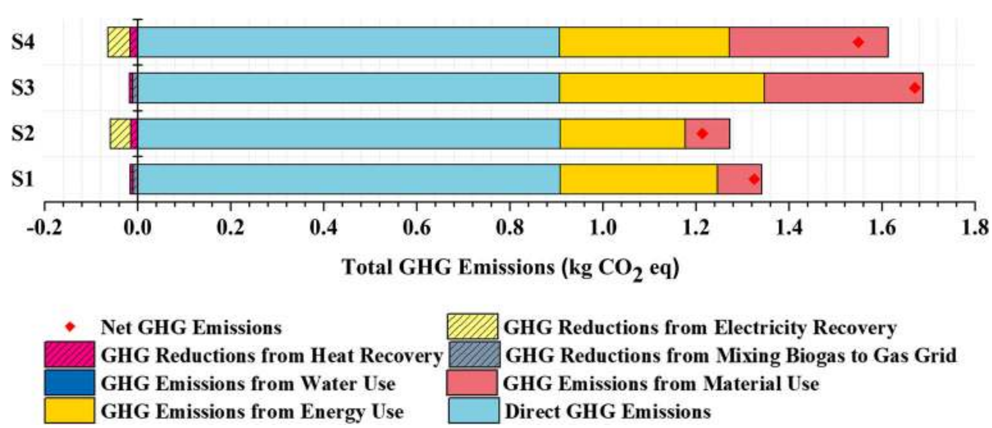

Fig. 2 Life cycle GHG emissions and contributions of energy, material, and water use and other sources

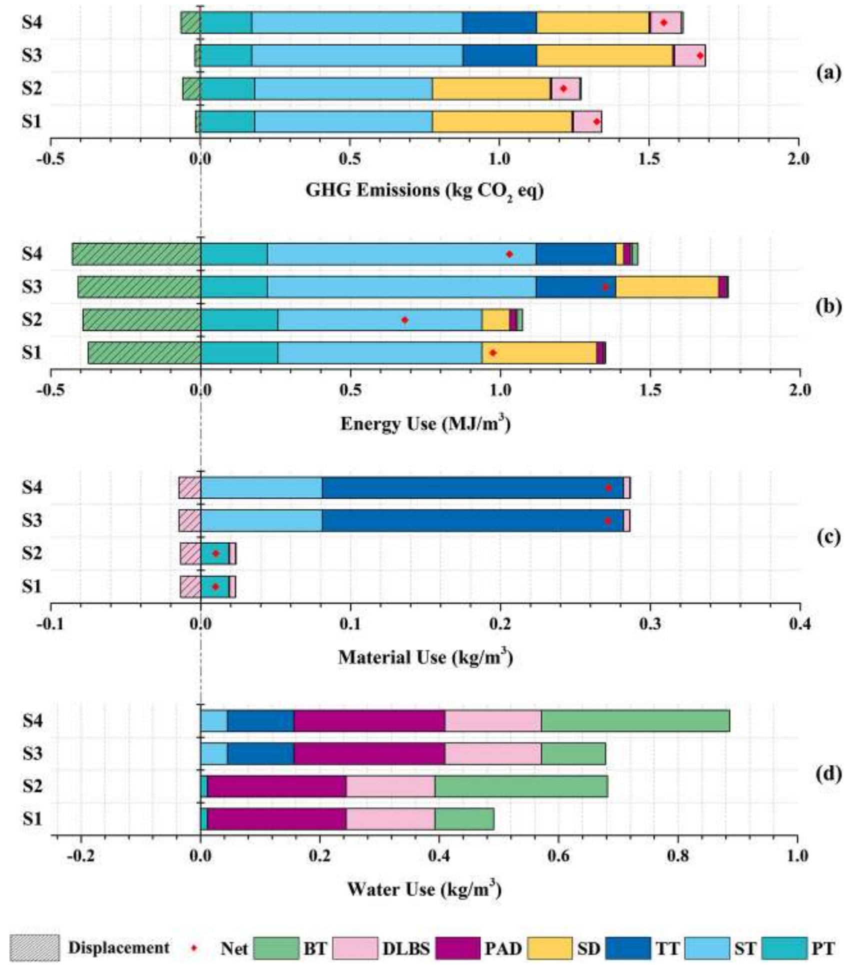

Fig. 3 GHG emissions (**a**), energy (**b**), material (**c**), and water (**d**) use by stages in the four scenarios. Negative values indicate reductions from displacement of material and energy use, and red dots denote net results

Eutrophication impact

Total eutrophication impact (positive value) in each scenario is estimated at: S1 (8.45E-03 kg Phosphate eq)≈S2 (8.43E-03 kg Phosphate eq)>S3 (7.09E-03 kg Phosphate eq)≈S4 (7.06E-03 kg Phosphate eq) (Fig. 4). The reason S3 and S4 perform better is mainly due to reduced TP as a result of the upgrade to meet the stringent standards. The ST stage contributes the most in S1 and S2, while the TT stage is the largest contributor in S3 and S4 (Fig. 4). This is mainly because ST and TT are the discharge stages of the treated wastewater, and water pollutants are the main contributor to eutrophication across four scenarios (Fig. 5a).

Besides water pollutants, other pollutants or processes also contribute to eutrophication impact. Due to N_2 emissions, the DLBS stage contributes more impact comparing with other sludge treatment stages (PAD and BT) (Fig. 5a), and so do N_2O emissions from ST and SD stages. The contribution of material use in the upgrade-WWTP scenarios is significantly higher than that in S1 and S2, due to $FeCl_3$ input from the newly added TT stage. Compared with the other three factors, energy use and water use contribute little to eutrophication impact.

As shown in Fig. 4, the order of eutrophication impact reduction (absolute value) is S4 (9.95E-04 kg Phosphate eq)>S3 (9.82E-04 kg Phosphate eq)>S2 (9.13E-04 kg Phosphate eq)>S1 (9.01E-04 kg Phosphate eq). This order is mainly due to the increase of eutrophication impact reduction by phosphate recovery in DLBS stage from increasing sludge output by upgrading (S4, S3>S2, S1), and the CHP system contributes more to eutrophication impact reduction than delivering biogas to gas grid (S4>S3, S2>S1). Overall, the reduced eutrophication impact due to resource recovery is far greater than different energy recovery techniques (Fig. 5b).

As Table 2 shows, the total net environmental benefit (NEB) in eutrophication of S3 and S4 (5.05E-02) is greater than that of S1 and S2 (4.87E-02). This result is attributed to the removal of water pollutants (the improvement of TP) by upgrading. The ST stage contributes the most to eutrophication impact reduction in all four scenarios, and for the two upgrade scenarios (S3 and S4), the contribution to NEB of

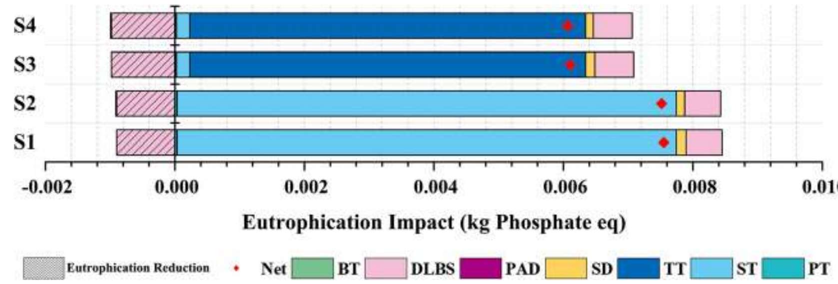

Fig. 4 Eutrophication impact of different stages in the four scenarios. Positive values denote impact, negative values denote impact reduction, and red dots denote the net results

TT stage is greater than that of PT stage (as shown in *Fig. S2a*). In terms of water pollutants, TP and TN are the main eutrophication pollutants in all the four scenarios, followed by COD (as shown in *Fig. S2b*). Because TP is not the only water pollutant with eutrophication impact and its contribution is less than the sum of the other two pollutants, the upgrading effect for excess TP in this study is limited in terms of reducing total eutrophication impact.

In total, the order of net eutrophication impact (Fig. 4) is S1 (7.55E-03 kg Phosphate eq)≈S2 (7.52E-03 kg Phosphate eq)>S3 (6.10E-03 kg Phosphate eq)≈S4 (6.07E-03 kg Phosphate eq). Therefore, in terms of eutrophication impact, employing the technical mean of upgrade in WWTP is superior to the mode shift of energy-resource recovery. Compared with S1 and S2, S3 and S4 reduce eutrophication impact by about 19%, mainly due to the contribution of water pollutants treatment, as analyzed above. And the scenario with energy-resource recovery and upgrade (S4) performs the best in eutrophication impact among the four scenarios.

Discussion

Given the results above, the environmental tradeoffs in our case of municipal wastewater treatment plant upgrade are identified. Compared with the baseline scenario (S1), the net GHG emissions of the other three scenarios are −8.41%, 26.07%, and 16.97% greater, and their net eutrophication impact is 0.45%, 19.16%, and 19.29% lower, respectively. Only the scenario with energy-resource recovery for existing WWTP would lead to GHG reductions, while the upgrading techniques (changing the process from CWSBR to BIOCOS and adding the tertiary treatment) would significantly increase GHG emissions. With regard to eutrophication, upgrading to treat excess TP could obviously reduce the impact more than energy-resource recovery. However, because TP is not the only water pollutant leading to eutrophication impact and its contribution is less than the sum of other pollutants, the degree by which eutrophication impact would be improved in the two upgrading scenarios (S3 and S4) is limited (~ 19%). Furthermore, a tradeoff solution between upgrading for better water pollutants treatment and energy-resource recovery for reducing energy and material consumption should be considered. In order to provide a reference for policymakers, the method of social and economic evaluation suggested by Song et al. (2018), or conjoint analysis suggested by Bai et al. (2018), could be applied in the future studies to identify the most environmentally friendly scenario.

Another major finding of our study is that for the different biogas utilization methods considered in this study, the CHP system is superior to the existing method of delivering biogas to gas grid, in terms of energy recovery or reduction of GHG emissions and eutrophication impact. However, S2 and S4 apply the CHP system to recover electricity and heat, under the assumption that the electrical, thermal, and total

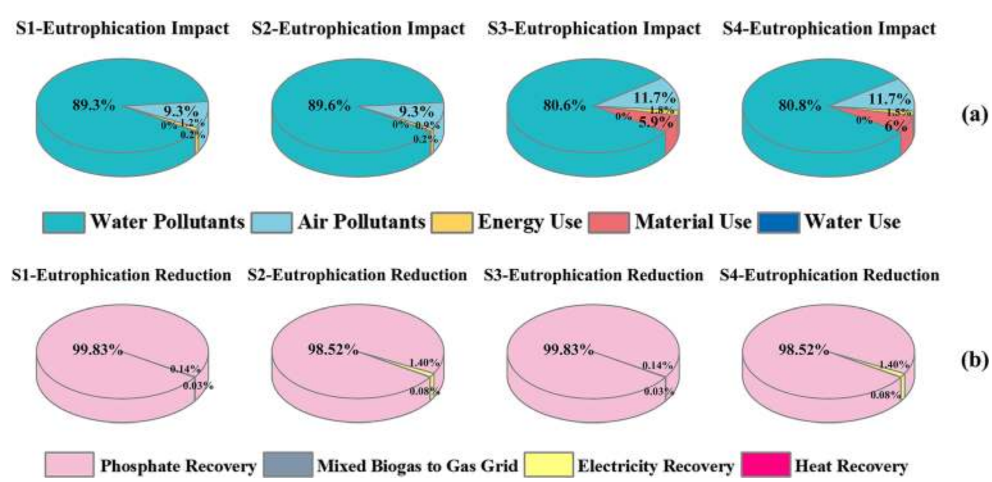

Fig. 5 The contribution of different factors in eutrophication impact (**a**) and eutrophication reduction (**b**)

Table 2 The net environmental benefit (NEB) of different scenarios (kg Phosphate eq)

Scenario	EI_0	EI_e	NEB
S1, S2	5.62E-02	7.55E-03	4.87E-02
S3, S4	5.62E-02	5.71E-03	5.05E-02

EI_0 denotes the eutrophication impact of direct discharge of incoming wastewater to water environment without WWTPs, EI_e presents the eutrophication impact of discharge of treated wastewater by WWTPs with or without upgrade, NEB indicates the eutrophication reduction caused only by water pollutants removal and its value equals to the difference value between EI_0 and EI_e

efficiencies are set as 40%, 50%, and 90%, respectively. The electricity self-sufficiency rates of the two scenarios are calculated to be 16.27% and 13.06%, respectively; in terms of heat recovery, both scenarios have surplus heat exported under the situation of meeting 100% heat self-sufficiency. Furthermore, neither the impact displacement from CHP system nor the biogas utilization of delivering to gas grid could offset the GHG impact in this study. According to Hao et al. (2019), thermal energy recovery from the water source heat pump played a significant role towards a net-zero impact on the total environment of WWTPs (contributing around 40%). Therefore, in the future, relevant WWTP and STP policymakers in the city may focus on improving the anaerobic digestion system for increasing biogas production and exploring the possibility of integrating with wastewater source heat pump to recover thermal energy, in order to have the opportunity to increase energy self-sufficiency rate and achieve net-zero environmental impact in the energy-resource recovery (Wang et al. 2016). In addition to the upgrade options above, the wastewater reuse alternatives for different purposes (e.g., Pintilie et al. 2016; Opher et al. 2019) could also help to reduce the environmental impacts of WWTPs. Meanwhile, the tradeoffs of these upgrade methods should be considered to inform decision-making according to our findings.

Compared with the findings of Awad et al. (2019), which considered similar wastewater treatment scenarios involving tertiary treatment and anaerobic digestion, there is a good agreement on the results of eutrophication impact. In terms of GHG emissions, the best performing scenario in the study by Awad et al. is the one including tertiary treatment and anaerobic digestion together, whereas in our study, the scenario with energy-resource recovery based on existing WWTP (S2) stands out. This is mainly because the present study considered GHG emissions embedded in both energy and material consumption, while Awad et al. neglected material use associated with various improvement techniques in the operational stage of WWTP. In our work, the consumption of $FeCl_3$ at the TT stage and acetic acid and Na_2CO_3 at the ST stage has a nonnegligible influence on GHG emissions under the condition of upgrading. Overall, these results suggest that chemicals or materials should be included in WWTP LCAs as they were sometimes omitted (Vera et al. 2015).

A limitation of our work is that only GHG emissions and eutrophication impact were considered in this LCA study. Although these are the two main environmental impacts associated with WWTPs, other impact categories such as marine aquatic ecotoxicity potential, human toxicity potential, and acidification potential could also be studied in future research. A comprehensive coverage of a wide spectrum of environmental impacts (e.g., Yang et al. 2012) can better reveal potential environmental tradeoffs involved in municipal wastewater treatment plants upgrade.

Conclusions

This study analyzed the life cycle GHG emissions and eutrophication impact of four wastewater treatment scenarios, namely, Existing-WWTP + STP (S1), Energy-resource Recovery for Existing-WWTP (S2), Upgrade-WWTP + STP (S3), and Energy-resource Recovery for Upgrade-WWTP (S4). Research results showed that upgrading (process changing from CWSBR to BIOCOS with tertiary treatment adding) the studied WWTP would reduce total eutrophication impact (~ 19%) and meet discharge standards for total phosphorus, but at the cost of increasing total GHG emissions (by at least 16%). The energy-resource recovery mode for existing WWTP (S2) had the lowest GHG emissions, and the WWTP with energy-resource recovery and upgrading (S4) performed the best in eutrophication impact. Compared with the mode shift of energy-resource recovery, upgrading would lead to lower eutrophication impact, mainly thanks to the contribution of water pollutants treatment.

For different biogas utilization methods, combined heat and power (CHP) system would outperform the existing method of delivering biogas to gas grid, resulting in greater energy recovery and lower GHG emissions and eutrophication impact.

Nomenclature PT, Primary treatment; ST, Secondary treatment; TT, Tertiary treatment; SD, Sludge disposal; PAD, Pretreatment and anaerobic digestion; DLBS, Digestion liquid and biogas slurry treatment; BT, Biogas treatment; COD, Chemical oxygen demand; BOD, Biochemical oxygen demand; SS, Suspended solids; TN, Total nitrogen; NH_3-N, Ammonia nitrogen; TP, Total phosphorus; BIOCOS, Biological combined system; CHP, Combined heat and power; CWSBR, Constant water level sequencing batch reactor; GHG, Greenhouse gas; LCA, Life cycle assessment; NEB, Net environmental benefit; PAM, Polyacrylamide; STP, Sludge treatment plant; WWTP, Wastewater treatment plant

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-021-13004-7.

Availability of data and materials The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Authors' contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by SS and HH. SS, HM, FY, and YZ prepared the first draft. AAK and YY participated in critical revision of the manuscript. All authors read and approved the final manuscript.

Funding This study was supported by the China Scholarship Council and Liaoning Major Scientific Technological Special Project (2019JH1/10300001).

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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