Environmental impacts assessment of wastewater treatment and sludge disposal systems under two sewage discharge standards: a case study in Kunshan, China

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Highlights:

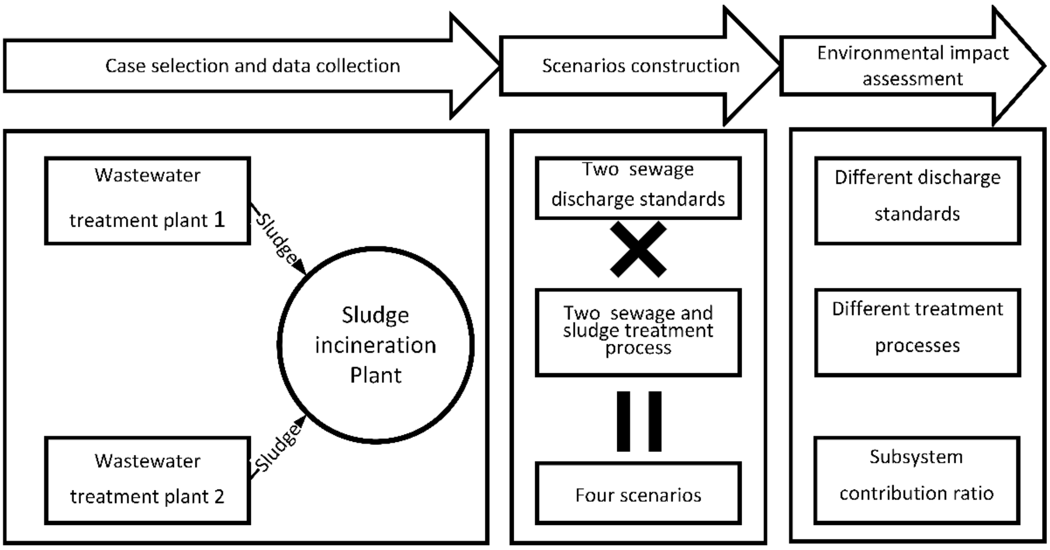
Reducing the moisture content of sludge is more important than raising sewage discharge standards.

Prioritize strengthening of physical treatment methods and reduce drug usage.

Energy recovery in the sludge incineration process is critical to system evaluation.

Stricter discharge standards should be accompanied by higher treated sewage reuse rates.

graphical abstract



Abstract:

To improve water quality in cities, the Chinese government has raised the discharge standard in many areas from class 1B to the more stringent 1A. Therefore, sewage treatment plants must ramp up their advanced treatment. Sludge disposal system is an extension of the sewage treatment system and has a significant impact on the effectiveness of sewage treatment. The environmental impacts of two sewage treatment plants and a sludge incinerator plant in Kunshan, China were evaluated using the life cycle assessment method, and the results of the two standards were compared under four scenarios. Our results show that improving sewage discharge standards can reduce eutrophication potential of the two systems by 4% and 14%, respectively, but the impacts on fossil energy depletion, global warming potential, human toxicity, freshwater ecological toxicity, and acidification potential are increased by 40% to more than 100 times. Further analysis reveals that it is necessary to decrease the moisture content of the dewatered sludge from 80% to 60%, because it has a significant impact on fossil energy depletion. In addition, physical methods should be prioritized over chemical agents for the advanced treatment and clean energy should be used in order to minimize trade-offs with other environmental impacts. The efficiency of energy recovery in the sludge disposal system is critical to the total environmental impact of the entire system which offers opportunities for improvements.

Keywords: discharge standards, life cycle assessment (LCA), sewage and sludge treatment, advanced treatment

1. Introduction

Due to the negligence of environmental issues in the past decades in China under fast economic growth, the water environment problem now has seriously hindered China's further development (Buonocore et al., 2018). Among them, the black and odorous water (BOW), a general term for water that exhibits unpleasant colors or smells, is very harmful to human health. Therefore, the Chinese government has issued an action plan for the prevention and control of water pollution. The goal is to limit the ratio of BOW within 10 percent in urban built-up areas by 2020 (State Council of China, 2015).

The discharge standards (SDSs) of many WWTPs have been formally upgraded from class 1B to 1A. By raising the sewage SDSs in WWTPs, the total amount of pollutants entering rivers can be reduced. The maximum emission of chemical oxygen demand (COD), biological oxygen demand (BOD), suspended solids (SS), total nitrogen(TN) and total phosphorus (TP) are 60, 20, 20, 20, 20 and 1 mg/L respectively in class 1B, and 50, 10, 10, 15 and 0.5 mg/L respectively in class 1A (MEP, 2002). The original design of many WWTPs in China did not take into account discharge standards upgradation, which can lead to obstacles for future improvement of the water environment (Wang et al., 2015). For example, many WWTPs were built inside the city, and since there was not enough land available for upgrading the treatment process, this leads to higher resource consumption. Sewage treatment can cause a variety of environmental impacts, and focusing on improving the water quality may increase the burden in other environmental categories (Li et al., 2013).

Sustainable development is the theme of future development. For city managers, sustainable development needs to consider the infrastructure of overall resource consumption, of which water resources are crucial (Ahmad et al., 2016) (Beery and Repke, 2010). In 2018, China's total water consumption was 6.0155E+11 m^3. Of this, 8.599 E+10 m^3 was domestic water, corresponding for 14.3% of the total while industrial water consumption was 1.2616 E+11 m^3, accounting for 21.0% of the total, and it was mainly consumed in the city (MWR, 2018). There are infrastructures for collection and treatment after discharge.

The WWTPs are used to remove pollutants in sewage and to protect water ecosystems. Due to the material and energy consumption, the wastewater treatment process has impacts on both air and solid pollution. The biochemical treatment stage of sewage and the sludge disposal stage can lead to greenhouse gas (GHG) emissions. It shoud be noted that diminishing marginal returns of pollution reduction as the treatment level increases (Lu et al., 2017). Therefore, a comprehensive analysis of this process is needed. Life cycle assessment (LCA) is the most common tool for environmental sustainability analysis of production systems at different scales, from single products to national and regional levels. Many researchers have applied LCA approach to investigate the environmental impacts of sewage and sludge treatment because of its holistic consideration (Bai et al., 2019) (Kacprzak et al., 2017). Li et al. showed that the energy structure of cities is crucial for the environmental impacts of the wastewater treatment process (Li et al., 2013). The power generated from coal accounts for a large share of China's energy mix, and it generates significant amount of indirect emissions of GHG. Masuda et al. investigated GHG emissions from different wastewater processes, and they claimed that the oxidation ditch treatment performed the best (Masuda et al., 2018).

The final destination of sewage sludge mainly includes the application on arable land, sanitary landfill, and secondary usage in building materials (Raheem et al., 2018). Different sludge disposal methods lead to huge differences in environmental impacts. Liu et al. conducted a life cycle inventory (LCI) to investigate the GHG emissions of six scenarios involving various sludge treatment technologies and disposal strategies, and they suggest that local governments should promote the use of composted sludge as urban greening fertilizers (Liu et al., 2013). Chen et al. proposed that the combined combustion of municipal solid waste and sludge is a better choice after evaluation with the LCA method (Chen et al., 2019). Sewage sludge contains large concentrations of nitrogen and phosphorus which can be applied as fertilizers for plants. Nevertheless, it also comprises different pollutants, which include inorganics, organics, and pathogens (such as heavy metals, microplastic, and polycyclic aromatic hydrocarbons) (Siebielska, 2014). Therefore, long-time land spreading of sludge may lead to the accumulation of contaminants in agricultural soil and adversely affect ecosystems. Despite the growing emphasis on sludge recycling, incineration appears to be the option for an increasing number of countries in Europe (Raheem et al., 2018). In China, it is not economical to treat sewage sludge into standard fertilizers. Direct landfills take up more land, while sludge incineration to recover energy is more economical. Furthermore, Incineration can recover the organics and convert part of the heat into electric energy. At the same time, incineration can reduce 90% sludge volume and almost all pathogens. The residual ash from sludge incineration can be disposed into the landfills or can be used in building materials (Xinyu et al., 2020).

The Chinese government passed an amendment in 2006, stating that SDSs class 1A must be implemented at places identified as national and provincial ‘priority watersheds and lakes’ (Wang et al., 2015), which implies WWTPs upgradation. Until now, the Jiangsu Provincial Government has completed upgrading all sewage treatment plants and is still advancing the construction of treated sewage ecological purification facilities, such as artificial wetlands. Due to the short period from decision-making to implementation completion, there are many areas for improvement. Therefore, it is necessary to systematically assess the overall environmental impacts of WWTPs and sludge incinerators as a single integrated system. In this work we select and assess the environmental impacts of two common methods of process upgrading in WWTPs. We use LCA methodology to compare the environmental impacts of different emission standards and upgrade measures, and further identify the advantages and disadvantages of different processing options.

2. Methodology

2.1. Life Cycle Assessment and Goal

The life cycle assessment(LCA) methodology is currently widely used to perform a holistic assessment of the environmental impacts on the systems (ISO, 2006b). Under this framework, the comparisons of technological systems are consistent. Holistic thinking and analysis of the systems is crucial in the LCA framework (ISO, 2006a). For a product, the life cycle is the entire production system, consisting of many consecutive and interlinked stages, from raw material acquisition or generation from natural resources to final disposal. LCA evaluates the potential environmental impacts of the inputs, outputs and a product system throughout its life cycle. Therefore, the assessment should include all life cycle phases. A cradle-to-grave attributional LCA was performed in this study to assess the environmental impacts of wastewater treatment and sludge disposal in Kunshan, P.R. China under different SDSs. The study uses treated wastewater as a product. The functional unit is defined as treatment of 1000 m^3 of wastewater eventually discharged into the river according to the discharge standards, with the incineration of the resulted sludge and the transportation of the incineration residues to the special waste treatment center. We evaluate the environmental impacts of two WWTPs and a sludge incinerator plant as a system in Jiangsu Province, China.

The treatment of sewage and sludge requires a lot of energy, and the source of electricity in this case study is coal combustion. At the same time, this process consumes a lot of chemicals that may be toxic, and the discharge of treated sewage into the river is also an important cause of eutrophication. Therefore, six different environmental impact categories are considered in this study: Abiotic depletion of fossil fuels, global warming potential (GWP100a), human toxicity (HT), freshwater aquatic ecotoxicity (FWAE), acidification potential (AP), and eutrophication potential (EP). Abiotic depletion of fossil fuels is related to the Lower Heating Value (LHV) expressed in MJ per kg of m^3 fossil fuel. The reason for considering the LHV is that fossil fuels are regarded as fully substitutable.

The characterization of elementary flows was done using the methodology CML World 2000. CML World 2000 methodology is working on a hybrid input-output model, which is useful for dealing with missing data in the LCA context. This hybrid model can be used to simulate full interactions between selected processes and the broader economy (Guinée and Lindeijer, 2002). Since China lacks specialized databases, Ecoinvnt 3.5 (2018) was used as the database for the background data. We also collect the published research data that are in line with our research.

2.2. Systems definition

Two WWTPs and a sludge incinerator in Kunshan, Jiangsu province, China, were selected for this study. The daily treatment scales of Wusongjiang wastewater treatment plant (WWTP1) and Beicheng wastewater treatment plant (WWTP2) are 50,000 m^3 and 150,000 m^3, respectively. The treatment processes of the two systems are shown in Fig. 1. Both systems are divided into five subsystems. In the past, these two WWTPs implemented the class 1B SDSs, and they adopt the two-level treatment process, which was pretreatment and biotreatment. To fulfill the more stringent class 1A SDSs, the advanced treatment (third level treatment) needs to be implemented after the biological treatment (MEP, 2002). The treated sewage can be discharged to the river after ultraviolet disinfection. In Jiangsu province, more than 65% of the sludge is incinerated (Fang et al., 2019). The sludge from those two WWTPs is sent to the same sludge incineration plant for incineration and disposal in this case. The sludge incineration is done by thermal drying. The sludge is semi-dried, and its moisture content (MC) is reduced to 60% before incineration, and then the sludge can be incinerated without external input of energy (Abuşoğlu et al., 2017). Besides, to ensure the stability of combustion power generation, coal is usually added to co-combustion power generation. Incineration residues are then transported to the special waste treatment center.

In our analysis, the WWTPs and sludge incineration plant's construction and demolition stages are not included in the LCA. One reasoning for this exclusion is that compared with the operation stage, the environmental impacts of the construction demolition stages are negligible (Hao et al., 2019b). On the other hand, the environmental impacts of the construction and demolition stages are mainly affected by the service time. Therefore, it is difficult to obtain reliable data for these two stages based on our functional units.

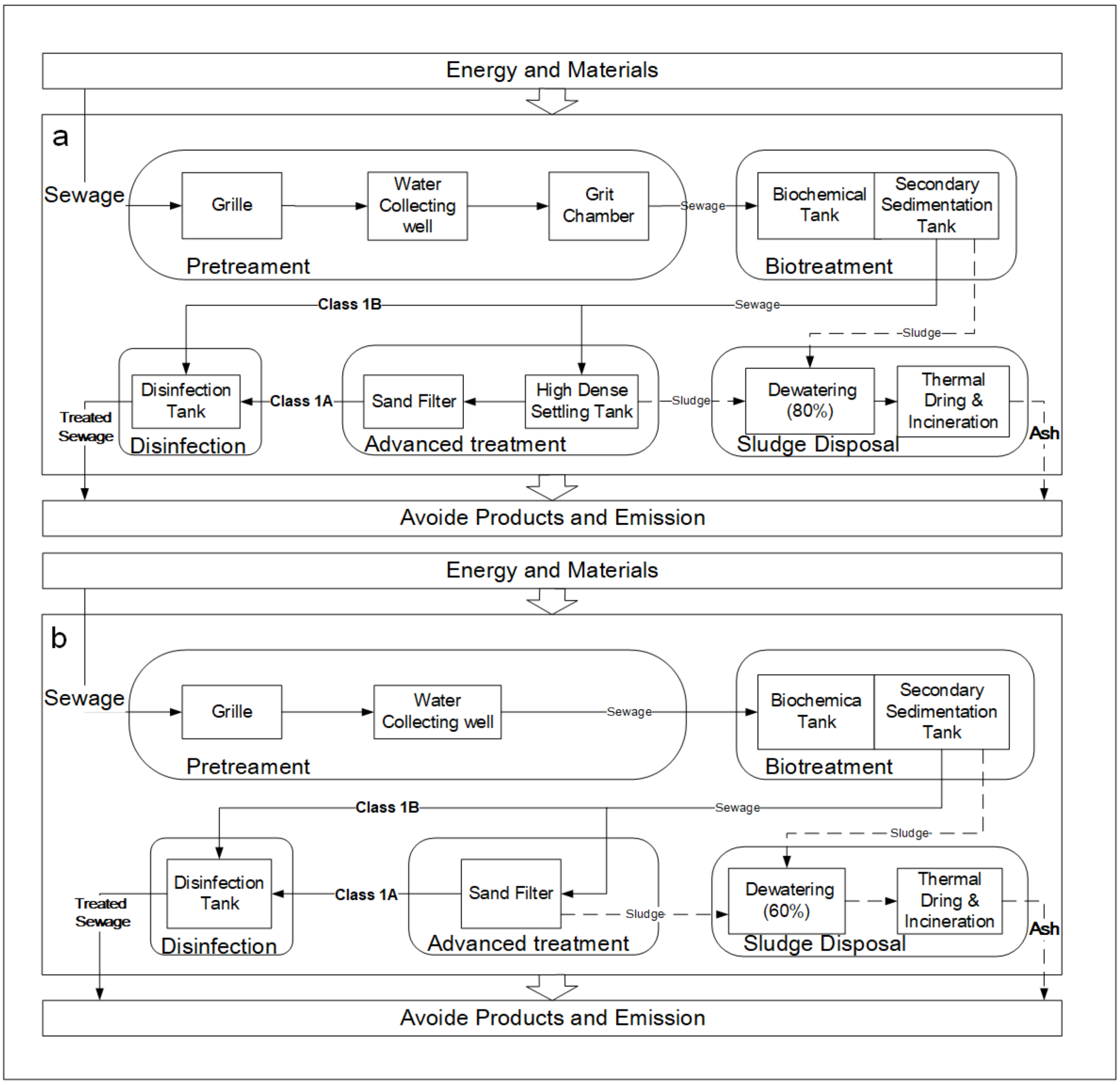


Fig. 1. System boundaries of the study. (a) treatment processes in WWTP1 and sludge incineration plant. (b) treatment processes in WWTP2 and sludge incineration plant. Note: avoided products means the useful application of waste or by-products.

2.3. Scenarios construction

The four scenarios considered in this study are described below: Scenarios 1 (S1), the SDS is class 1B. The disinfected sewage is discharged into river after biological treatment at WWTP1, and the sludge with moisture content 80% from WWTP1 is incinerated for disposal. Scenarios 2 (S2), the SDS is class 1A. The disinfected sewage is discharged into river after advanced treatment at WWTP1, and the sludge with moisture content 80% from WWTP1 is incinerated for disposal. Scenarios 3 (S3), the SDS is class 1B. The disinfected sewage disinfected is discharged into river after biological treatment at WWTP2, and the sludge with moisture content 60% from WWTP2 is incinerated for disposal. Scenarios 4 (S4), the SDS is class 1A. Sewage disinfected discharge into river after biological treatment at WWTP2, and the sludge with moisture content 60% from WWTP2 is incinerated for disposal. Further, an overview of the comparison of the four scenarios is shown below in Table1.

The processing methods adopted in the four scenarios are shown in Fig. 1. In these four scenarios, the sludge from the WWTP is incinerated in the same sludge incineration plant. The standard requirement of moisture content of sludge after dewatering is not higher than 80% (MEP, 2002). Furthermore, WWTP1 and WWTP2 have different pretreatment processes. The actual incoming and outgoing water qualities in various scenarios are shown in Table 2

Table 1. The characteristics of the four scenarios

Scenarios	WWTP	Treatment Process	SDSs	Sludge MC
S1	WWTP1	pretreament+biotreatment	class 1B	80%
S2	WWTP1	pretreament+biotreatment+advanced treatment	class 1A	80%
S3	WWTP2	pretreament+biotreatment	class 1B	60%
S4	WWTP2	pretreament+biotreatment+advanced treatment	class 1A	60%

Note: sewage discharge standards (SDSs); moisture content (MC)

Table 2. Incoming and outgoing water quality in various scenarios.

Items	**COD (mg/L)**	**BOD (mg/L)**	**SS (mg/L)**	**TP (mg/L)**	**NH_3-N (mg/L)**	**TN (mg/L)**
WWTP1 inflow	193.71	93.26	100.14	2.62	21.23	24.04
scenario 1 outflow	17.14	3.42	7.14	0.18	0.31	7.20
scenarios 2 outflow	14.57	3.11	5.14	0.13	0.20	6.45
WWTP2 inflow	135.40	118.00	88.09	2.66	20.10	25.50
scenario 3 outflow	23.17	0.00	8.00	0.68	0.34	10.04
scenario 4 outflow	20.00	3.70	7.00	0.25	0.14	10.07

Note: chemical oxygen demand (COD), biological oxygen demand (BOD), suspended solids (SS), total phosphorus (TP), ammonia nitrogen (NH3-N), total nitrogen (TN)

2.4. Life cycle inventory

The life cycle inventory comes from three sources: field measurements, calculated according to the available data, and references to other studies. Each scenario can be divided into five subsystems with different processes, and the life cycle inventory is obtained by counting the input and output of each process. The inventory data of all the treatment processes are shown in Tables 3 and 4. Among them, the power consumption of each treatment process in the WWTP is calculated and counted according to the running power and functioning period of the electric equipment. The dosage of Poly aluminum chloride (PAC), polyacrylamide (PAM), and other chemicals in the sewage treatment process are determined according to the user record in the WWTPs. Both WWTPs are purchased from a manufacturer that is located 150 km away. In 2018, 5.06E+11 kWh of electricity was generated in Jiangsu, and more than 90% was generated by thermal power (Ding et al., 2017). Therefore, we assume that our plants are powered by coal, and the life cycle inventory of coal power is based on the study of Ding et al. (Ding et al., 2017). The water qualities at three places in the WWTP are tested, including raw sewage, secondary sedimentation tank effluent, and disinfection tank effluent. Meanwhile, the composition of the sludge was also tested. The organic matter content of sludge was similar in the four scenarios.

The whole system is divided into five parts, namely pretreatment, biological treatment, advanced treatment, disinfection, and sludge disposal (see Fig. 1). WWTP1 adopts the pretreatment technology of grille combined settling tank, while in WWTP2 the settling tank is replaced by a grille with smaller clearance. The biological treatment of the two WWTPs is Anaerobic - Anoxic Oxic (AAO). The direct emission of GHG from AAO process comes mainly from two sources: CO_2 generated by microbial endogenous respiration and organic matter oxidation, and the N_2O generated by microbial digestion and denitrification (Lu et al., 2017). According to the results presented by Chai et al. (Chai et al., 2015), under similar operating conditions, AAO process directly discharged 223.177Kg CO_2 and 0.710 Kg N_2O per 1000 m^3 of sewage treated. WWTP1 includes a high dense settling tank to remove solid particles from sewage before biological treatment, while WWTP2 does not have this treatment. In this study, for the advanced treatment, it is used a coagulation and precipitation technology. The removal object of this process is the organic and inorganic pollutants in the colloidal and micro-suspension state in sewage., Nitrogen and phosphorus are as well removed, and these two chemical elements can lead to eutrophication of water (Hamoda et al., 2004). Between 50% and 80% of the Biochemical Oxygen Demand (BOD) value in the effluent after biological treatment is from suspended particles. Therefore, in this study, the increased sludge volume in the advanced treatment stage is estimated according to the suspended solids (SS) value of biological treatment and advanced treatment sewage, as well as the dosage of drugs including PAC and PAM. These agents promote the flocculation and sedimentation of particles in the sewage and will eventually be intercepted by the sand filter and enter the sludge. The calculation is as follows:

$$\mathrm{SA} = \mathrm{TS} + \mathrm{M}_{H2O}$$
$$\mathrm{TS} = (SS_2 - \mathrm{SS}_3) + \mathrm{PAC} + \mathrm{PAM}$$
$$\mathrm{M}_{H2O} = 4 * \mathrm{TS}$$

where SA is the sludge with moisture content 80% or 60% generated by advanced treatment, TS is total solids; SS_3 and SS_2 are the suspended solids of the sewage after biotreatment and advanced treatment, respectively; PAC and PAM are the quantities of drugs added to the advanced treatment; M_{H2O} is the weight of water in the SA.

During the sludge disposal stage, the two WWTPs adopted the method of dewatering by the plate and frame filter press, but the moisture content of the dewatered sludge was different. Moisture contents of the Dewatered sludges from WWTP1 and WWTP2 are 80% and 60%, respectively. After the disposal stage, the sludge was then transported by truck to the same sludge incinerator for burning to generate electricity. GHG emissions from the sludge disposal stage are calculated based on two considerations: first, the emissions caused by coal combustion are added in the process of sludge incineration; second, the emissions from sludge combustion are calculated based on the chemical elements of the sludge. Since sludge incinerators contain mixed sludge with different moisture content, the input and output of the sludge incineration stage in this study were based on the life cycle inventory of scenario 3 in Dong et al. 's study, where the moisture content of the sludge is 80% (Dong et al., 2014). The energy balance was calculated according to the change of sludge moisture content (Hao et al., 2019a). It is estimated that burning one tonne (t) of sludge with 60% moisture content can produce 3511kwh, and sludge with 80% moisture content can produce 982kwh electricity.

Table 3. Life cycle inventory of operation stage for scenarios 1 and 2.

Process	**Input**	**Amount**	**Output**	**Amount**
	Pretreatment			
Grilles	electricity (kWh)	0.77		
water collecting well	electricity (kWh)	31.38		
grit chamber				
	Biotreatment			
biochemical &secondary sedimentation tank	electricity (kWh)	69.28	CO_2 (t)	0.22
			N_2O (t)	0.0007
	Advanced treatment			
high dense setting	PAM (t)	0.0002		
	PAC (t)	0.0335		
	transportation (tkm)	5.05		
	electricity (kWh)	50.91		
	Disinfection			
disinfection tank	NaClO (kg)	0.0077		
	electricity (kWh)	8.50		
	Sludge disposal			
dewatering step	lime (kg)	4.62	S1 sludge (t)	0.72
	dehydrant (kg)	44.26	S2 sludge (t)	0.91
	electricity (kWh)	61.58		
incineration-1tonnes	coal (t)	0.9000	S1&S2 ash (t)	0.60
	hydrogen chloride (kg)	6.10	CO_2 (t)	1.58
	sodium hydroxide (kg)	5.40	N_2O (t)	0.0002
	limestone (t)	0.0700	SO_2 (t)	0.0123
	electricity (kWh)	213.20	S1&S2 electricity	982.00
	transportation (tkm)	30.00	S3&S4 electricity	3511.00
	transportation (tkm)	441.32	S1&S2 Heat (MJ)	11800.00
			S1&S2 Heat (MJ)	24230.00

Note: Unlabeled data means that the two scenarios have the same data.

Table 4. Life cycle inventory of operation stage for scenarios 3 and 4.

Process	**Input**	**Amount**	**Output**	**Amount**
		Pretreatment		
Grilles	electricity (kWh)	1.92		
water collecting well	electricity (kWh)	32.64		
		Biotreatment		
biochemical &secondary sedimentation tank	electricity (kWh)	101.76	CO_2 (t)	0.2232
			N_2O (t)	0.0007
		Advanced treatment		
sand filter	Transportation (tkm)	12.08		
	PAC	0.0800		
	PAM	0.0005		
	electricity (kWh)	39.28		
		Disinfection		
disinfection tank	electricity (kWh)	12.00		
		Sludge disposal		
dewatering step	Lime(kg)	22.22	S3 sludge（ton）	0.15
	PAM	0.0890	S4 sludge（ton）	0.2

*See Table 3 for the sludge incineration inventory.

3. Result and discussion

3.1. Environmental impact under different discharge standards

We present in Fig.2 the normalized results of the environmental impact assessment of two WWTPs under different discharge standards. When the two standards are implemented in WWTP1, the eutrophication potential with S2 decreased by less than 4%, which is directly due to the advanced treatment and the lower amount of pollutants entering the natural water from WWTPs (see Fig. 2a). This indicates that stricter discharge standards are beneficial to improve the water environment which is in line with other studies like Wang et al (Wang et al., 2015). However, the results also indicate that higher standards can lead to a shift of the environmental impacts. Compared to class 1B, both the fossil energy consumption and GWP100a with class 1A increased by more than 40%, since the advanced treatment leads to more electricity consumption and produces more sludge, which results in more GHG emissions (Monea et al., 2020). In terms of human toxicity potential and freshwater ecological toxicity, the results in S2 are 5 times and 13 times higher than S1, respectively. The direct reason for the results is the use of PAC, PAM and other chemicals in the advanced treatment process. In terms of the impact of acidification potential, our analysis indicates that it is more than 40% higher in S2 than in S1. This might be due to higher consumption of coal and electricity since in Kunshan's electricity is mainly generated by burning coal. The type of electric energy is very important for the results of WWTP's LCA, and (Wang et al., 2015) recommend that more clean energy should be used in the future.

In 2019, thermal power is still the main source of electricity production in China, and coal is the most important raw material. Referring to the trend from 2011 to 2019 in China, the proportion of thermal power has decreased year by year, while clean energy such as nuclear power, solar power, wind power, and hydropower has increased gradually. By 2019, thermal power accounted for 68.9% of the country's total power generation. Nuclear power, solar power, wind power, and hydropower accounted for 4.8%, 3.1%, 5.5%, and 17.8% according to China Electric Power Yearbook 2020. The development of hydropower resources is greatly restricted by geographical conditions. It is foreseeable that the proportion of nuclear power, solar and wind energy will further increase in the future, and thermal power may still be dominant in the next few decades. Therefore, through the incineration of sludge, the recovery of the energy and the reduction of the consumption of coal and other fossil energy in thermal power have a significant contribution to reduce various environmental impacts.

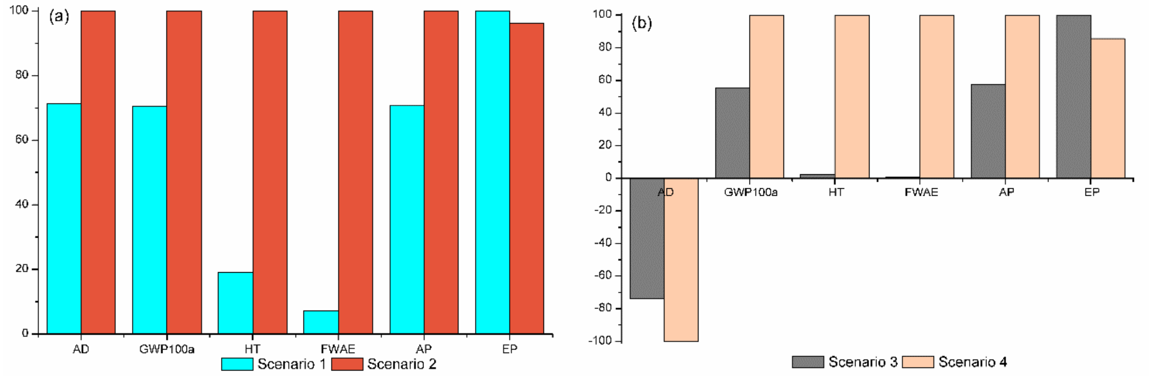


Fig. 2. Characterized impacts of (a) Scenarios 1 and 2, (b) Scenarios 3 and 4. (percentage values; data from Table S1 in the supplementary information). Note: Abiotic depletion of fossil fuels (AD), Global warming (GWP100a), Human toxicity (HT), Freshwater aquatic ecotoxicity (FWAE), Acidification potential (AP), Eutrophication potential (EP). When comparing the same environmental impacts of the two scenarios, the larger one is treated as 100, and the corresponding proportion of the other one is calculated.

As shown in Fig. 2(b), when two different discharge standards are implemented in WWTP2, they can result in significant differences in environmental impact categories between S3 and S4. The eutrophication potential of S4 was 14% lower than that of S3. The water qualities of inflow and outflow sewage in four scenarios are given in Table 1, and the results show that the effluent quality of WWTP2 is improved significantly. S4 compared to S3, in terms of the environmental impact of GWP100a and acidification potential, increased by more than 45%. And 42% respectively. At the same time, in terms of human toxicity and freshwater ecological toxicity, they are 44 times and 132 times higher than those without advanced treatment, respectively.

The reason for this is the use of many chemicals in the advanced treatment process. Most commercial polymers are also extracted from petroleum raw materials, and most of the chemicals used in the processing process are not environmentally friendly. Besides, most synthetic polymer structures are biodegradable, but biodegradation is usually extremely slow (Bolto and Gregory, 2007). The results suggest that more stringent SDSs have contributed to reducing eutrophication but lead to adverse effects on almost all other environmental impacts. Stricter SDSs will reduce the impact on the environment in some ways, but will also dramatically increase operating costs. Managers should weigh the relationship between the environmental benefits brought by the improvement of SDSs and the social cost of investment from a global perspective.

It is unwise to directly discharge the treated sewage into the river. In China, the sewage that meets the Class A discharge standard is close to the standard for urban sewage recycling, such as water quality standard for green space irrigation, industrial use and urban miscellaneous water consumption. In some cases, if sewage can be used instead of tap water, the environmental impact of this treatment process will be greatly reduced (Lyu et al., 2016). The "13th Five-Year Plan" national urban sewage treatment and recycling facilities construction plan requires that by the end of 2020, China needs to add 1.505E+07 m^3/d of recycled water facilities. In 2018, China's sewage treatment rate reached 95.49%, which has a huge potential for reuse in the context of the improvement of sewage discharge standards.

3.2. Environmental impacts of different treatment processes under the same sewage discharge standards

The sewage treatment processes adopted by the two WWTPs are different, which leads to different environmental impacts with the same SDSs. Fig. 3a shows the differences between S1 and S3 on environmental impact categories, both of which are subject to class 1B SDSs. The results indicate that S1 is superior to S3 only in terms of eutrophication potential. In other aspects, lower environmental impacts are detected in S3. For instance, environmental impacts, such as GWP100a, human toxicity potential, freshwater ecological toxicity, and acidification potential are five times higher in S1 than in S3. It should be noted that despite the implementation of the same SDSs, the inflow and outflow data of the two WWTPs are different. Even small improvements in effluent quality by current standards require significant energy and resource input. In the past, when class 1B standard was implemented in WWTPs, the focus is on the removal of chemical oxygen demand (COD). This will help reduce the impact of the difference in water quality between incoming and outgoing sewage on the evaluation of each scenario and make the evaluation more objective. Fig. 3b is drawn according to this principle. Therefore, we compared this environmental impact of S1 and S3 in removing COD per mg/L over the life cycle. The results are shown in Fig. 3b, and it shows that the effect of S1 on water eutrophication was further reduced, only 37% of that of S3. In terms of the greenhouse effect, human toxicity potential, freshwater ecological toxicity, and environmental impacts of acid rain. The gap between S1 and S3 is narrowed. Therefore, we can conclude that the environmental impact of eutrophication potential in S3 is higher than in S1. However, the environmental impacts of other categories in S3 are lower than those in S1.

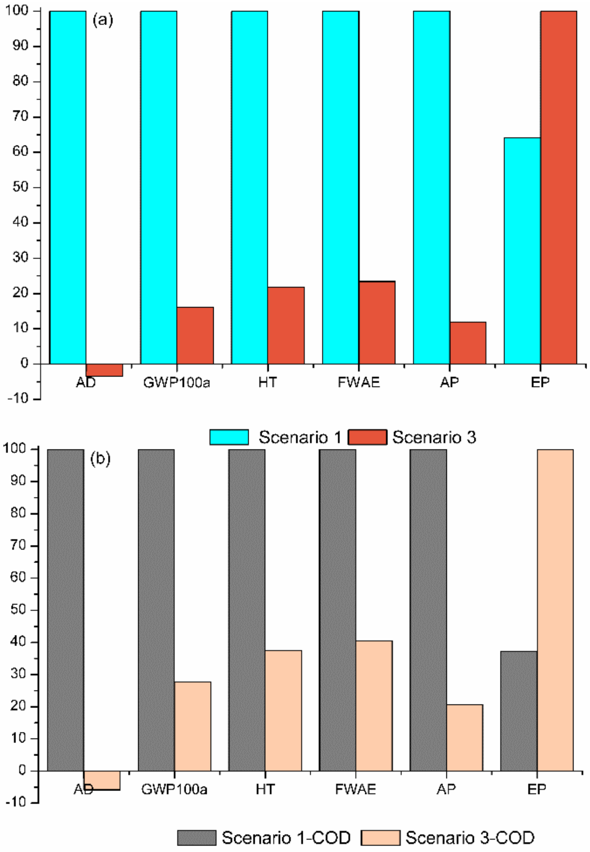


Fig. 3. Characterized impacts of (a) scenarios 1 and 3, (values are in percentage; data from Table A.1). And characterized impacts of (b) removing per mg/L COD in scenarios 1 and scenario 3 (values are in percentage). By comparing the differences between influent and effluent in the same scenario, we can obtain the value of the reduction in pollutant concentration. Dividing the environmental impact value by the reduced pollutant concentration can get the environmental cost of reducing the unit concentration of COD.

Fig. 4 shows the difference in the environmental impacts between S2 and S4. As the effluent water quality of S2 is better than that of S4, the environmental impact of S2 on eutrophication potential is nearly 30% lower than that of S4. However, in terms of fossil energy depletion, GHG emissions, and acidification potential, the results are much worse in S2 than those in S4. This might be due to different disposal methods in the sludge disposal stage in those two scenarios. The impacts on human toxicity and freshwater ecotoxicity are approximately twice larger than those of S1, and these might be due to the increased use of chemical agents.

In China, the primary goal of adopting advanced treatment is to solve the problem of water environmental pollution in cities, among which eutrophication of water is the focus. As mentioned above, nitrogen and phosphorus are the main sources of water eutrophication. In S2 2.48mg/l of TP and 21.03mg/l of ammonia are removed from the water, while in S4 2.41mg/l of TP and 20mg/l of ammonia are removed from the water. Since the removal efficiency of the two is similar, the comparative analysis of unit pollutant removal is not carried out. In general, there are pros and cons with S2 and S4. For instance, the effluent effect of S2 is better, but the higher energy consumption leads to other environmental problems. The heavy use of chemicals in S4 leads to its worse performance in human toxicity potential and freshwater ecological toxicity. In the past, the design of sewage treatment plants did not consider the removal of trace pollutants, and there is still a lack of information about these pollutants (Rahman et al., 2018). An important task of advanced processing is to solve these problems, so it is necessary to reduce the use of chemical agents (Pesqueira et al., 2020). Natural organic flocculants based on polysaccharides or natural polymers are natural products and more environmentally friendly. Compared with traditional chemical flocculant, bioflocculant is a safe and biodegradable polymer with considerable shear stability, and it is easy to obtain from renewable agricultural resources, and will not produce secondary pollution (Bolto and Gregory, 2007). Bioflocculant is a promising alternative to conventional flocculant. Natural polymers have also the problems of high cost and short shelf life because of biodegrading over time (Lee et al., 2014). Therefore, it is necessary to holistically evaluate the environmental impact of each process to compare with each other, and further improve the system.

The significant difference between S1 and S3 is also caused by fossil energy consumption, S2 and S4 are the same. The advanced treatment increases the sludge output as shown in Tables 2 and 3. A large amount of fossil fuels is consumed during the system operation, such as electrical energy consumption during operation and fuel consumption during transportation. When the sludge is incinerated, part of the thermal energy generated by the combustion of organic matter in the sludge is converted into electricity output system, which is often referred as avoiding products. Due to the lower moisture content of sludge in S3 and S4, the electricity generated by the calorific value of sludge combustion is greater than fossil fuel consumed in the whole process. Although the absolute value is small, the whole process is output energy to the outside of the system.

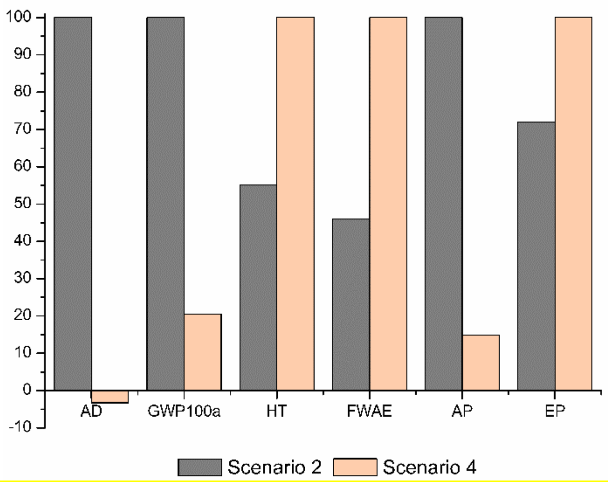


Fig. 4. Characterized impacts of scenarios 2 and 4 (values are in percentage; data from Table A.1).

3.3. Life cycle impact assessment of subsystem processing

It is very important to evaluate the environmental impact of each processing unit of the whole system because only in this way we can identify which units in the system have the greatest impacts on the environment. Based on these results, the system can be improved in terms of the technology and management. Fig. 5 shows the contribution of each processing part to different types of environmental impacts in S2 and S4. The specific contribution value of each processing process is given in Table A. 2. Firstly, the disposal of sludge under S2 is the subsystem that consumes the most fossil energy, accounting for more than 80% of the energy used by the whole system. On the contrary, sludge treatment under S4 saves 39555 MJ of fossil energy. The difference between the two scenarios in sludge treatment is that the moisture content of the sludge after dehydration is different as discussed in Section 3.2. In the subsequent sludge incineration process in S2, the moisture content in the sludge is high, which requires extra energy, and thus reduces the system's electricity generation (Sever Akdağ et al., 2018). On the contrary, the content of dry matter in sludge with moisture content 60% is twice than that of 80%, and it has a higher amount of organic matter in the sludge. By reducing the moisture content of sludge, energy recovery efficiency can be greatly improved, more thermal energy can be used to generate electricity, and the environmental impact of fossil energy consumption can be reduced in disguise. Regarding transport of the same dry matter, sludge with 80% moisture content is twice the weight of the sludge with 60% moisture content, resulting in greater energy consumption during transportation. A promising option in future is the integration of wastewater treatment and incineration plants, which would make full use of waste heat generated by sludge incineration plants and further reduce fossil energy consumption (Nakatsuka et al., 2020). Furthermore, it eliminates the environmental impact from transport of the sludge. Due to the above-mentioned reasons, among the greenhouse effect, sludge disposal in S2 contributed the most to the whole system, reaching 88%. In S4, sludge treatment, advanced treatment, and biological treatment have a significant impact on GHG, accounting for 23%,38%, and 28% respectively. Therefore, as highlighted by Tan et al., reducing the moisture content of sludge mechanically to between 40% and 56% is the most favorable energy recovery for incineration (Tan et al., 2017).

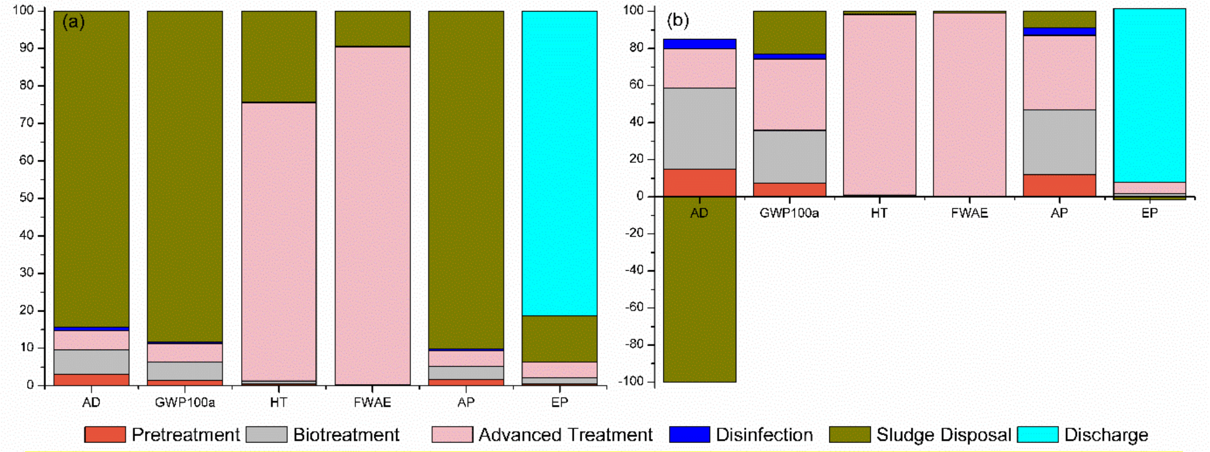


Fig. 5. Contribution analysis by processes (a) S2 and (b) S4 (values in percentage; data from Table A. 2). The inputs and outputs from each process affect six different environmental impact categories. Different color means the contribution of each processing part to different types of environmental impacts in S2 and S4.

A possible alternative can be is solar drying of the sludge. Solar greenhouse drying technology is characterized by reduced land requirements compared with traditional outdoor drying beds, as well as by low-energy requirements compared with other thermal drying methods (Boguniewicz-Zablocka et al., 2020). But it still requires a lot of lands compared to direct incineration. Process operation is cost-efficient, with close to no maintenance, and observed specific evaporation rates up to threefold higher than conventional drying beds. However, this approach has one major drawback: drying efficiency depends on the degree of irradiation and temperature, which vary throughout the year (Boguniewicz-Zablocka et al., 2020).A potential solution is to adopt the membrane bioreactors (MBRs) to reduce the production of sludge. However, MBRs have shortcomings of high energy consumption and high consumables (Zheng et al., 2018), and these shortcomings need to be overcome.

The main source of GHG emissions from sludge treatment is the combustion of organic matter in the sludge, while the GHG emissions from advanced treatment and biological treatment are mainly due to the consumption of electric energy and pollutant conversion. There were three significant sources for GHG emissions, namely, direct emissions of CO_2 from aerobic treatment of wastewater and sludge incineration, direct N_2O emissions from wastewater treatment, and indirect emissions from electricity use (Chai et al., 2015). Mainly occurs in the three subsystems of biological treatment, advanced treatment, and sludge disposal. And the sludge incineration stage also will produce a lot of GHG emissions, mainly in the flue gases. Flue gases typically contain CO_2, NO_x, and SO_x (mainly SO_2). Microalgae can convert CO_2, the main component of flue gas, into biomass and lipids via photosynthesis at a high rate. Similarly, sulfur and nitrogen are essential elements for microalgal growth (Du et al., 2019). But this method needs to further increase the growth rate of algae to be feasible. N_2O is produced in biological treatment subsystems during autotrophic nitrification and heterotrophic denitrification. Many conditions will affect this process, mainly :(1)Aeration, (2) Transition between anoxic and aerobic conditions, (3)The effect of nitrate, free nitrous acid, and pH, (4) carbon sources (5) Availability of copper ions (Law et al., 2012). The goal of reducing N_2O production can be addressed through the design and operational management of wastewater treatment plants. These design features include influent flow balancing, high recycling rates, large bioreactor volumes, and long solids' retention time (Foley et al., 2010).

For human toxicity and freshwater ecological toxicity, advanced treatment in S2 and S4 contributed the most. However, it is worth mentioning that these two aspects in S4 are about two times bigger than those in S2. Due to insufficient land reserved during the construction of the sewage treatment plant. When the discharge standard is upgraded, the WWTP2 does not have enough land to build a high dense settling tank. To ensure effluent quality, the amount of chemical agents used is increased. The acidification potential value in S2 contributes also the most to the sludge disposal stage. The contribution of each treatment part to the acid potential in S4 is similar to the greenhouse effect, mainly due to the thermal power generation adopted by Kunshan. For the current system, the efficient energy recovery of the sludge disposal system is the key to reducing the environmental impact of the system (Hao et al., 2019c). Comparing the contribution of eutrophication potential value in S2 and S4, the importance of reducing the moisture content of sludge was proved again.

Through the comparative analysis of various influencing factors of each treatment process, we find that priority should be given to physical methods to reduce the chemical agents for advanced treatment. Second, the moisture content of dewatered sludge has a great influence on the whole system. Therefore, it is crucial to raise the standards for the moisture content of WWTPs.

4. Conclusion

In this work, we assess the environmental impacts of two sewage treatment plants and a sludge incinerator plant in Kunshan, China using LCA methodology. These results of the two standards were compared under four scenarios in order to identify the advantages and disadvantages of different processing options.

We find that improving sewage discharge standards can reduce eutrophication potential of the two systems by 4% and 14%, but with many times sacrifice of impacts of fossil energy, GWP100A, human toxicity, freshwater ecological toxicity, acidification potential. We recommend that when raising the sewage plant discharge standards, it is necessary to decrease the moisture content of the sludge from the sewage plant. Lower sludge moisture content will not only save energy loss during transportation but also increase energy outputs from sludge incineration. In the next ten years, China may still rely on thermal power that consumes fossil energy, so this measure is crucial to reducing the environmental impact of the entire system. Increasing the reuse rate of sewage and replacing part of tap water are important measures to reduce environmental impact. In the process of sewage treatment, priority should be given to physical methods to remove pollutants. In the long run, reducing the use of chemical agents will bring enormous environmental benefits in terms of human toxicity and freshwater ecotoxicity. Under the premise of ensuring the quality of the effluent water, both reducing the amount of sludge produced through operation management and technical improvements can reduce the GHG emissions of the system.

Acknowledgments

The authors acknowledge the support provided by the Industrial Ecology Programme at Norwegian University of Science and Technology and School of Civil Engineering at Southeast University of China.

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