How are typical urban sewage treatment technologies going in China: From the perspective of life cycle environmental and economic coupled assessment

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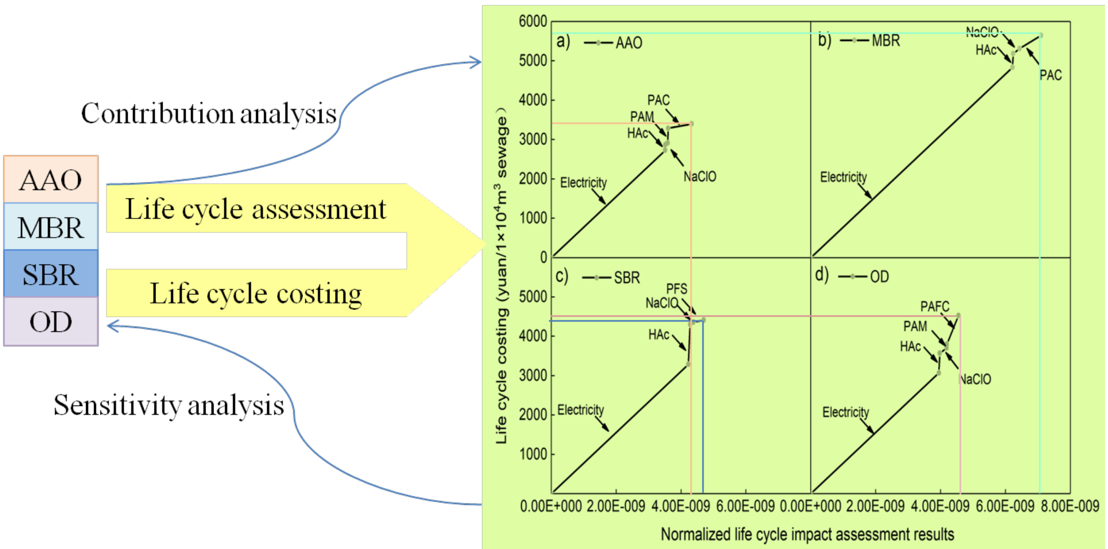
Abstract

Sewage treatment is an important public service, but it consumes a lot of energy and chemicals in the process of removing wastewater pollutants, which may cause the risk of pollution transfer. To find the corresponding hot issues, this paper took the lead in integrating life cycle assessment (LCA) with life cycle costing (LCC) to evaluate four most typical sewage treatment technologies with more than 85% share in China. It is found that anaerobic/anoxic/oxic (AAO) was the optimal treatment scheme with relatively small potential environmental impact and economic load. The normalized results show that the trends of the four technologies on eleven environmental impact categories were basically the same. Marine aquatic ecotoxicity potential accounted for more than 70% of the overall environmental impact. Contribution analysis indicates that electricity and flocculant consumption were the main processes responsible for the environmental and economic burden. Overall, electricity consumption was the biggest hot spot. Sensitivity analysis verifies that a 10% reduction in electricity could bring high benefits to both the economy and the environment. These findings are expected to provide effective feedback on the operation and improvement of sewage treatment.



Keywords: Life cycle assessment; Life cycle costing; Technical comparison; Environmental impact; Contribution analysis; Sewage treatment technology

1. Introduction

Sewage treatment project is an important part of modern urban public infrastructure, which is responsible for solving water pollution problems. With the rapid growth of China's economy and population, the number and capacity of sewage treatment plants are growing well, doubling in just ten years from 2006 to 2016 (MOHURD 2018). Various sewage treatment technologies and equipments have been invented and applied. Sewage treatment can greatly reduce the pollutants in the influent wastewater and obtain good effluent quality, thus reducing the impact on the water environment. However, the gas and solid waste discharged in the treatment process, as well as the input of energy and chemicals, will have extra negative impacts on the environment (Zang et al. 2015). In addition to paying attention to the effluent quality and pollutant removal rate, the environmental impact of different treatment technologies should also be evaluated reasonably, which has important theoretical value and practical significance for guiding the design and operation of sewage treatment (Cheng et al. 2020)..

Life cycle assessment (LCA) is a technology to quantify the environmental impact of all phases of a product, service, or process. Since the 1990s, LCA has been applied in the field of sewage treatment (Emmerson et al. 1995; Singh et al. 2019), and it has proven to be an ideal tool to evaluate the environmental impact of sewage treatment plants (Guest et al. 2009). Initially, LCA was used to calculate the environmental impact of a particular case and identify key phases (Emmerson et al. 1995; Pasqualino et al. 2009). Later, LCA was gradually applied to compare different scenarios of a single treatment system, such as comparison of effluent standards (Bai et al. 2018; Zhao et al. 2018), comparison of different sewage reuse rates (Raghuvanshi et al. 2017; Tong et al. 2013), comparison of different sludge disposal methods (Murray et al. 2008; Xu et al. 2014), and comparison of different evaluation methods (Hernández-Padilla et al. 2017; Vera et al. 2015). Up to now, multiple systems have been compared gradually. For example, Kamble et al. (2019) conducted a life cycle assessment of six local sewage treatment technologies in India, and the results showed that the soil biotechnology had the least environmental impact, while the aerated lagoons were the opposite.

With the continuous development and improvement of LCA, life cycle costing (LCC) was added to the life cycle sustainability assessment (LCSA) for economic impact assessment (Swarr et al. 2011). LCA is a widely recognized environmental management tool. However, when making the final decision, it is necessary to consider both environmental factors and economic differences between diverse technologies. LCC can compensate for the lack of LCA in economic evaluation by calculating the total cost in the life cycle, which is helpful to identify the production links with large economic load. Therefore, integrating LCC and LCA allows for better evaluation and comparison of products.

However, most of the current researches in China generally had the following shortcomings: (1) focus on the comparison between two plants in the terms of technical or economic, failing to get more comprehensive evaluation results (Hao et al. 2019; Zhao et al. 2019)(Zhang et al., 2019); (2) basically concentrated on analysis of energy (Li et al., 2020), carbon emissions (Chai et al. 2015), sludge disposal (Innocenzi et al., 2020) and water reuse (Li et al., 2020), ignoring the more detailed identification of hotspots; (3) lack the comparative studies of various localized technologies, and unable to put forward optimization suggestions in line with China's national conditions further.

In this context, this paper integrated LCC and LCA to evaluate the four typical regional sewage treatment technologies: anaerobic/anoxic/oxic (AAO), membrane bioreactors (MBR), sequence batch reactors (SBR) and oxidation ditches (OD) in China. According to researches, more than 85% of sewage treatment plants in China adopt four technologies mentioned above (Jiang et al. 2020; Li et al. 2018). The samples were selected from one of the most developed cities in China, representing the overall level of sewage treatment in country. The study aims to (1) quantify the environmental and economic impacts of typical urban sewage treatment technologies in China, (2) identify the key impact categories, phases, processes and substances for improvement, (3) establish geographically specific data on Chinese urban wastewater treatment to provide useful information for decision makers in their effort to build and transform the sewage treatment industry from environmental and economic perspectives.

2. Methodology

2.1. Life cycle assessment

LCA is a method to evaluate the potential environmental impact of a product system in its whole life cycle. According to the ISO 14040 standard (Finkbeiner et al. 2006; ISO 2006a, b), LCA is generally divided into four steps: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA) and interpretation of results.

2.1.1. Definition of goal and scope

The goal of this study was to analyze the life cycle of four most typical and widely used sewage treatment technologies (AAO, MBR, SBR and OD) in China. LCA can identify hot spots in the product lifecycle to find the potential of pollutant mitigation and enable decision-makers to make strategic planning.

Sewage treatment is a particularly large and complex system, and previous studies have shown that the effects of the construction and demolition stages are negligible compared to the operation stage (Garcia-Montoya et al. 2016; Hospido et al. 2012; Lundie et al. 2004; Rodriguez-Garcia et al. 2011). Canaj et al. (2021) and Xue et al. (2019) confirmed that electricity consumption and chemical consumptions contributed up to 90% of the environmental loads to most impact category indicator results. Rashid et al. (2020) verified the environmental impact was largely derived from electricity consumption and chemical consumptions (57–95%) and construction and demolition only contribute less than 10% in each impact category. A similar finding was reported by (Foley et al., 2010) and (Hao et al., 2019) that the operation of WWTP contributed more than 90% to environmental impact categories compared with construction and demolition phases. Therefore, this study only considered the operation stage from sewage pumping into the plant to final discharge. With the treatment of 1×10^4 m^3 of sewage as a functional unit, a system boundary was established as shown in Fig.1. The research scope included primary treatment, secondary treatment, advanced treatment, and sludge treatment, so as to compare the environmental load of each treatment phase of the four technologies.

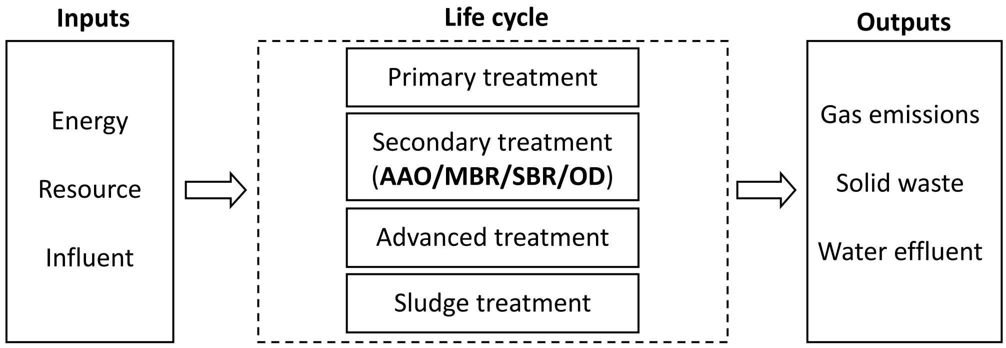


Fig.1. System boundary for the LCA study. AAO: Anaerobic/anoxic/oxic; MBR: Membrane bioreactor; SBR: Sequencing batch reactor; OD: Oxidation ditch.

2.1.2. Inventory analysis

This study selected four representative wastewater treatment plants for specific inventory in Wuxi, Jiangsu Province. As one of the biggest demonstration areas and most developed cities, these samples basically represent the best level of sewage treatment and the future development direction (Cheng et al., 2020). All plants removed contaminants with the same treatment capacity, ensuring the comparability fundamentally. The inventory data of this study mainly came from field investigation, employee interviews and literature reports. The input items covered energy consumption, chemical consumption and transportation in each treatment phase. The output items involved pollutants in the effluent (biochemical oxygen demand (BOD_5), chemical oxygen demands (COD), ammonia nitrogen (NH_3-N), total nitrogen (TN), total phosphorus (TP) and suspended solids (SS)), waste gas (ammonia (NH_3), hydrogen sulfide (H_2S)), and solid waste (grid slag, sanding, biochemical sludge). Most were based on 2017 annual average data. The detailed inventory is shown in Table 1.

Table 1 Life cycle inventory of four sewage treatment technologies (functional unit: 1×10^4 m^3 sewage).

I/O for per phase	Parameter	Unit	AAO	MBR	SBR	OD
Primary treatment						
Inputs	Electricity	kWh	532.14	837.19	495.55	1150.32
	SS	Kg	1140	1520	1020.3	1023.9
	COD	Kg	3130	3060	1779	3346.8
	BOD_5	Kg	1110	1030	628.4	1528.6
	NH_3-N	Kg	224	245	240.4	279.6
	TP	Kg	28.6	37.1	24.7	45.8
	TN	Kg	265	326	306.1	347
Outputs	Grid slag	Kg	657.53	600.00	415.34	1000.00

	Sanding	Kg	383.56	400.00	276.16	450.01
	H_2S	Kg	0.0260	0.0844	0.0278	0.0019
	NH_3	Kg	0.1452	0.8504	0.2619	0.0192
Secondary treatment						
Inputs	Acetic acid	Kg	32.88	81.89	237.449	117.32
	Electricity	kWh	2219.61	5128.59	3235.21	2161.32
Outputs	H_2S	Kg	0.0553	0.0192	0.0523	-
	NH_3	Kg	0.2767	0.1918	0.5546	-
Tertiary treatment						
Inputs	Sodium Hypochlorite	Kg	67.19	181.48	91.32	193.18
	Electricity	kWh	693.19	-	199.43	276.27
Outputs	SS	Kg	70	20	30	50
	COD	Kg	210	187	298	209.9
	BOD_5	Kg	80	41	36	36
	NH_3-N	Kg	6.49	5	11.5	9.7
	TP	Kg	0.87	2.5	1.4	2.5
	TN	Kg	79.6	81.4	132.2	96.7
Sludge treatment						
Inputs	Poly aluminum chloride	Kg	821.92	750.68	-	-
	Poly aluminium ferric chloride	kg	-	-	-	364.13
	Poly ferric sulfate	Kg	-	-	71.23	-
	Polyacrylamide	Kg	8.22	-	-	6.81
	Electricity	kWh	56.02	235.65	282.83	347.50
Outputs	Biochemical sludge	Kg	3791.91	4928.97	2509.59	6488.52
	H_2S	Kg	0.0066	0.0472	0.0376	0.0031
	NH_3	Kg	0.0411	0.4745	0.3543	0.0308

As for transportation, it is assumed that both chemicals and wastes were transported by diesel-driven trucks, with a transportation distance of 50 km and 30 km respectively. The background data of upstream and downstream processes required for the study were from GaBi education database (version 9.1) and Ecoinvent database (version 3.6), mainly involving the production of electricity and chemicals as well as the transportation of chemicals and wastes. The relevant data representing China in the database were used preferentially. If not available, foreign parameters would be used.

2.1.3. Impact assessment

Life cycle impact assessment is a vital part of LCA. On the basis of the obtained inventory, the various types of data are associated with their corresponding environmental impacts by classification. Then data under the same kind of impact are unified into a single indicator for characterization, which represents the mid-point result. In order to make different impact categories comparable, the normalization can be conducted by comparing mid-point results with the specific pollutant levels of the region to obtain dimensionless values.

CML 2001 method (Guinee 2001) is currently the most popular and commonly used method of impact quantification due to its broad impact categories and accuracy (Gallego-Schmid and Tarpani 2019). Therefore, this study adopted CML 2001 to obtain the characterization and normalization results for each impact category in each scenario. The following eleven impact categories are included: abiotic depletion potential-elements (ADPE), abiotic depletion potential-fossil (ADPF), acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity potential (FAETP), global warming potential (GWP 100 years), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), ozone layer depletion potential (ODP), photochemical ozone creation potential (POCP), and terrestrial ecotoxicity potential (TETP). The global standard values based on CML 2001-Jan.2016 normalization system are listed in Table A.1 in Appendix.

2.1.4. Interpretation of results

The interpretation, which is a comprehensive analysis of the results of inventory analysis and impact assessment, can provide valuable suggestions for decision-makers in combination with research goal and scope.

2.2. Life cycle costing

LCC is an extended life cycle economic evaluation method based on LCA research (Woodward 1997), and the steps of the LCC approach are similar to those of LCA. Within the goal and scope defined by the LCA, LCC calculates the economic load generated in the whole life cycle process and identifies the main links. The unit price of each item was taken from the average price of the Chinese market. The related data were obtained on average, so no cash flow and discount rate can be considered, and then static economic analysis method-like was used in this paper. The detailed list can be found in Table A.2 in Appendix.

3. Results and discussion

3.1. LCIA results

Through the environmental impact assessment of the inventory data of four sewage treatment technologies, the mid-point values of each impact category were obtained after the characterization. As shown in Table 2, the minimum environmental impact values all occurred in the AAO and SBR scenarios, while the maximum values all occurred in MBR and SBR. For example, AAO had the least impact on acidification, eutrophication, freshwater aquatic ecotoxicity, human toxicity, and terrestrial ecotoxicity. MBR performed the worst in most environmental impact categories, such as abiotic depletion, acidification, global warming, human toxicity, marine aquatic ecotoxicity, ozone layer depletion, and photochemical ozone creation. As an advanced sewage treatment technology, MBR can obtain high effluent quality, but it is at the cost of consuming more chemicals and energy. These additional inputs easily lead to high negative environmental impacts. Therefore, it is necessary to achieve a balance between water pollution control and potential pollution transfer.

Table 2 Comparison of the characterized environmental results among the four technologies.

Category	Unit	AAO	MBR	SBR	OD
ADPE	kg Sb eq.	0.004	0.006	0.002	0.005
ADPF	MJ	50409.189	75923.651	47115.788	53150.747
AP	kg SO_2 eq.	18.160	29.975	18.600	19.106
EP	kg Phosphate eq.	53.786	58.274	73.325	62.999
FAETP	kg DCB eq.	36.555	58.552	119.644	48.834
GWP	kg CO_2 eq.	8832.495	12293.060	6989.533	11810.717
HTP	kg DCB eq.	1251.332	2053.547	1479.396	1348.672
MAETP	kg DCB eq.	821593.814	1304231.832	810468.542	967496.538
ODP	kg R11 eq.	3.01×10^{-11}	4.46×10^{-11}	2.03×10^{-11}	3.30×10^{-11}
POCP	kg Ethene eq.	1.635	2.525	1.590	1.767
TETP	kg DCB eq.	31.645	50.416	134.641	46.834

To compare the different impact categories, this study normalized the characterized results based on the CML 2001-Jan.2016 standard system. Fig.2 shows the normalized results. The impacts and trends of the four technologies on these eleven environmental categories were similar, but in terms of numerical values, AAO was relatively small in each category. In general, the normalized dimensionless values of

AAO, MBR, SBR, and OD were 5.72×10^{-9}, 8.85×10^{-9}, 5.92×10^{-9}, and 6.70×10^{-9} respectively. From the perspective of environmental categories, marine aquatic ecotoxicity potential provided the largest contribution to the overall impact, accounting for more than 70%, followed by human toxicity and eutrophication potential. In contrast, the values of abiotic depletion potential-elements and ozone layer depletion potential were too small and could be negligible, which is consistent with Hancock et al. (2012) and Tong et al. (2013).

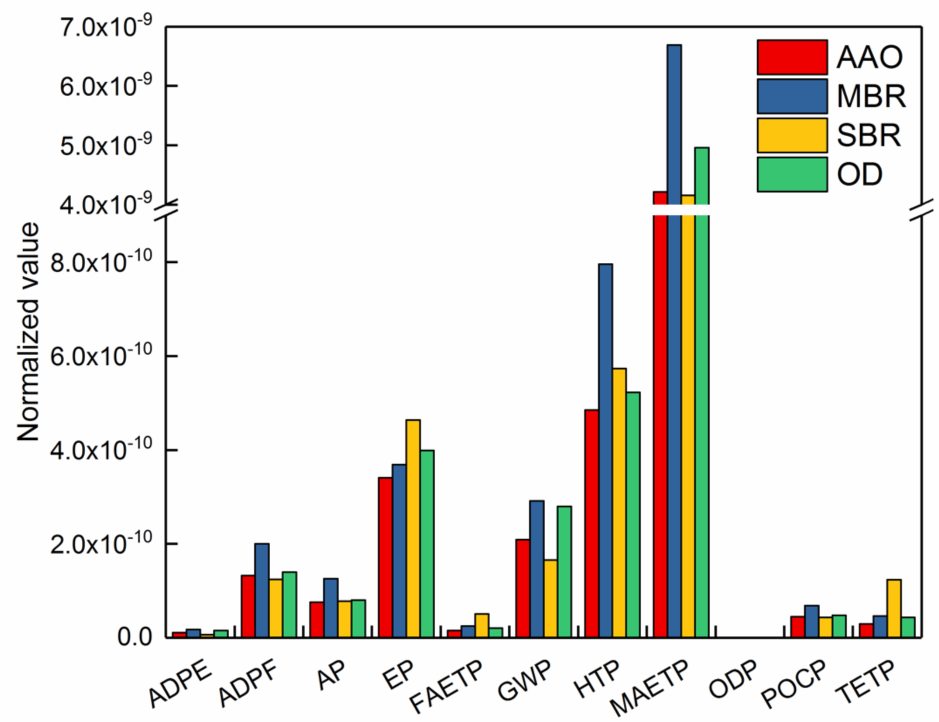


Fig.2. Comparison of the normalized environmental results among the four technologies.

3.2. Contribution analysis

In order to further explain the results, an impact contribution analysis was carried out to identify the main processes and key factors. Fig.3 and Fig.4 illustrate the contribution of different phases and processes to eleven environmental impacts in four scenarios.

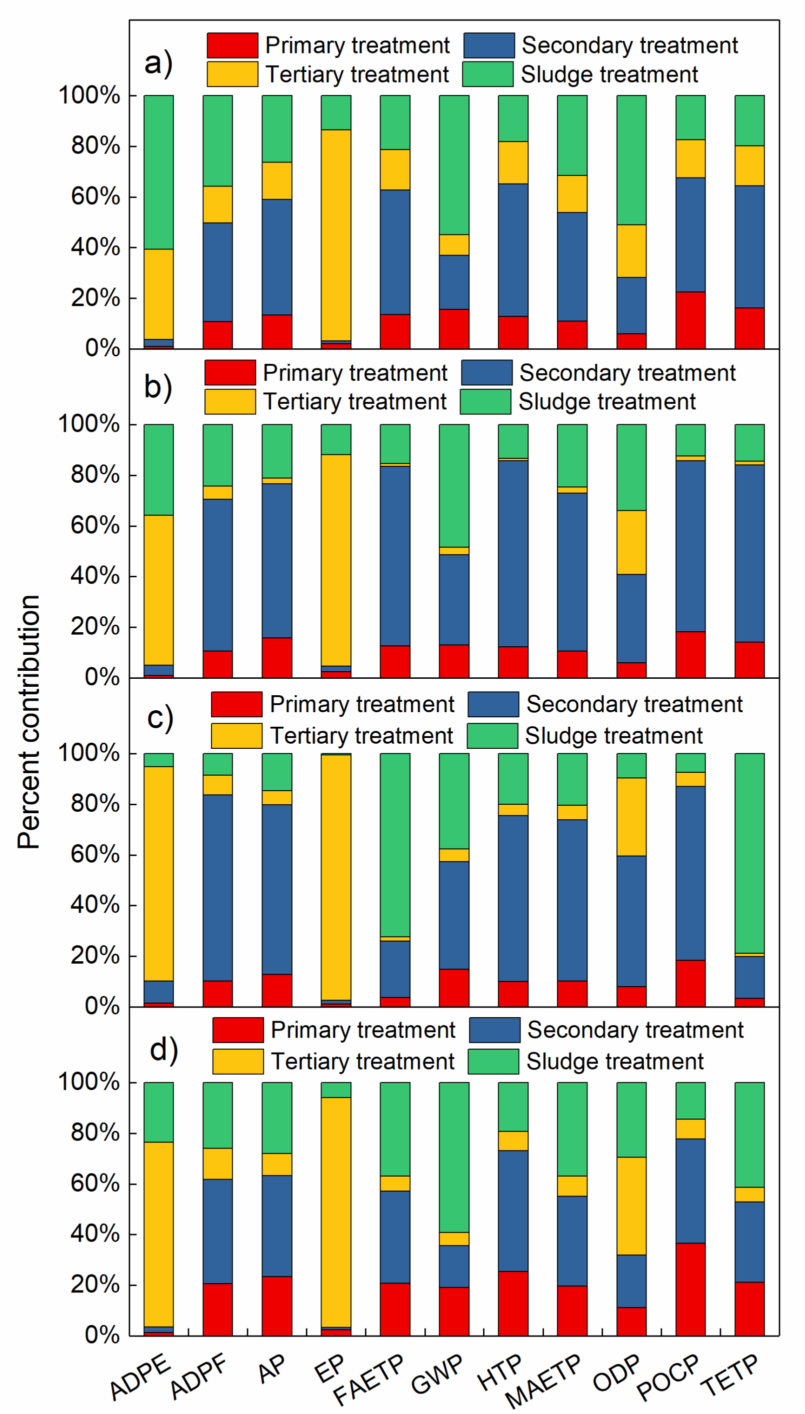


Fig.3. Phase contribution. a) AAO; b) MBR; c) SBR; d) OD.

As shown in Fig.3, the environmental impact was largely from the secondary treatment, while the impact of the primary treatment was relatively small. The main contribution phases of different impact categories were slightly different for the four technologies. It can still be found that secondary treatment was the main contributor to environmental impacts such as abiotic depletion potential-fossil, acidification, human toxicity, marine aquatic ecotoxicity and photochemical ozone creation, while eutrophication potential was mainly caused by advanced treatment.

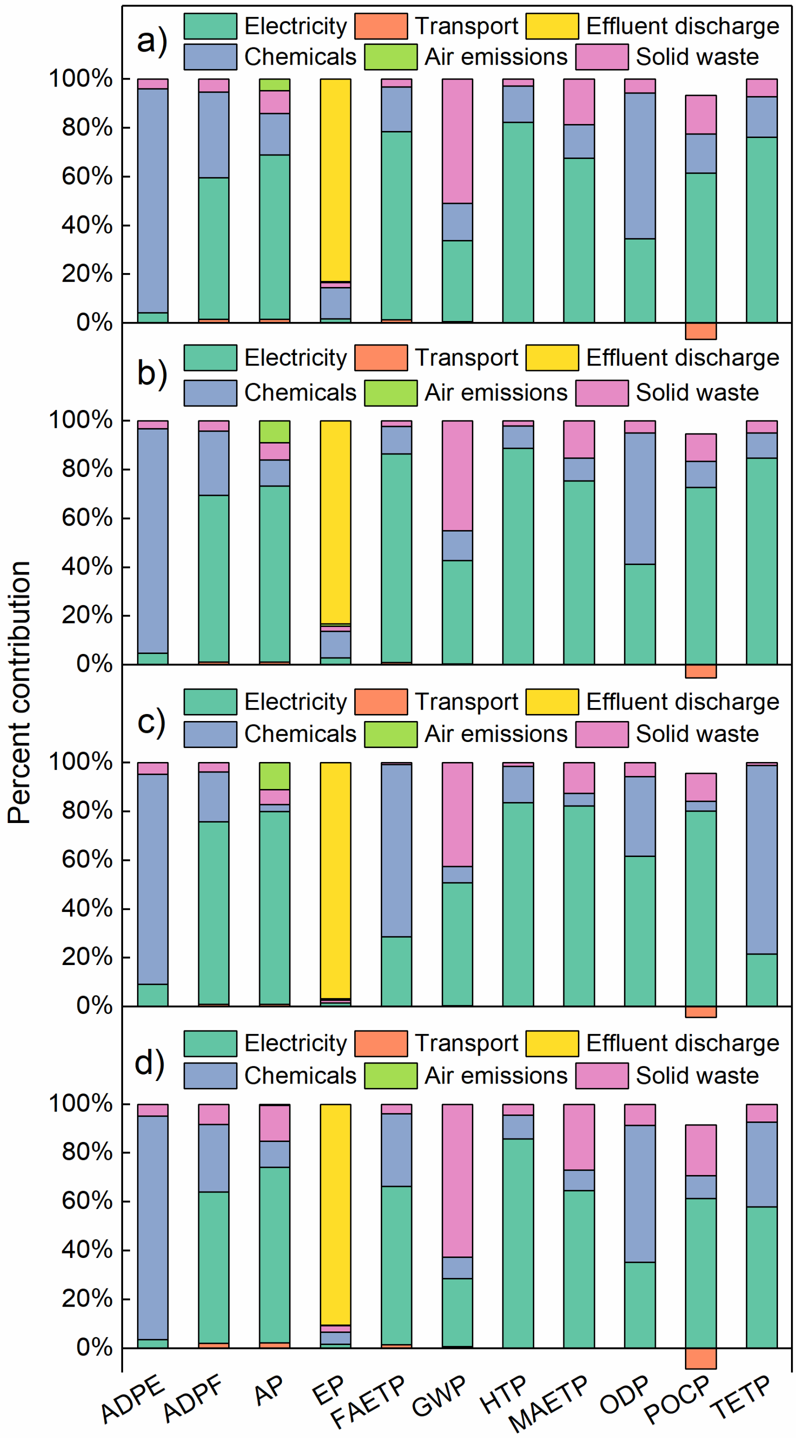


Fig.4. Process contribution. a) AAO; b) MBR; c) SBR; d) OD.

Fig.4 reveals that electricity consumption was the decisive factor leading to the impact categories of abiotic depletion potential-fossil, acidification, human toxicity, marine aquatic ecotoxicity and photochemical ozone creation potential. This is because China currently relies mainly on thermal power generation (NBS 2018), which will be accompanied by a large amount of raw coal consumption and pollutant emissions such as sulfur dioxide. It is a common finding in the sewage treatment, where electricity consumption tends to dominate most of the environmental impacts (Abello-Passteni et al. 2020; Polruang et al. 2018). Therefore, it should be noted that the use of clean and renewable energy may greatly reduce the whole life cycle environmental impact of sewage treatment (Li et al. 2013; Ye et al. 2018). Chemicals also made an important contribution to abiotic depletion potential-elements, freshwater aquatic ecotoxicity, ozone layer depletion, and terrestrial ecotoxicity potential. The dominant contributor to eutrophication was the effluent discharge because of the residual nutrients. Global warming potential was mainly attributable to solid waste. In this study, the end treatment of sludge was incineration, so there was a large amount of greenhouse gas emissions.

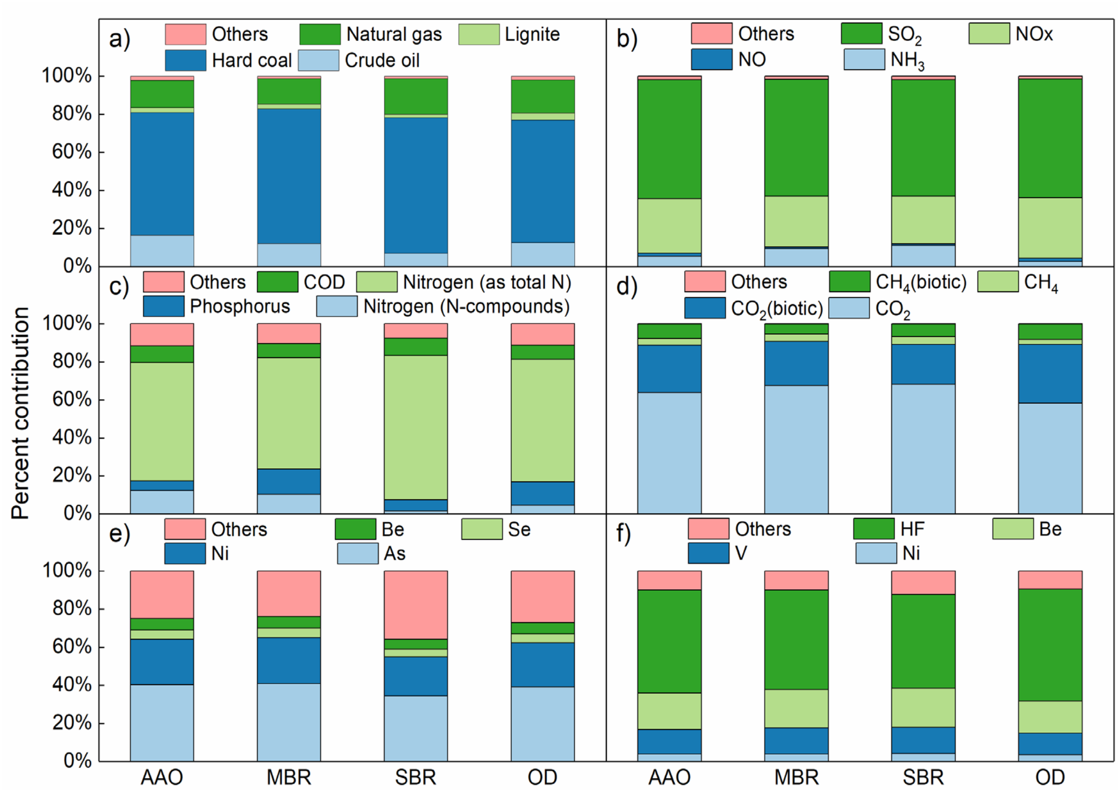


Fig.5. Substance contribution. a) ADP; b) AP; c) EP; d) GWP; e) HTP; f) MAETP.

To further analyze the key substances that cause environmental impacts in each link of sewage treatment, the six most affected environmental categories were selected based on the normalized results. Fig.5 shows the contribution of key substances under the four scenarios. The consumption of hard coal during power generation made the largest contribution to abiotic depletion. Sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emitted into the air were the key influencing factors of acidification. Total nitrogen (TN) discharged into fresh water was the main contributor to eutrophication. Carbon dioxide (CO_2) emitted into the air contributed the most to global warming potential. Arsenic (As) and nickel (Ni) were major contaminants of human toxicity. For marine aquatic ecotoxicity, hydrogen fluoride (HF) emitted in fresh water was the dominant contributor.

Combined with the contribution analysis of key phases, processes and substances, the impact categories are grouped and further discussed as follows:

(1) Abiotic depletion potential

Abiotic depletion potential is related to the exploitation of non-renewable resources (Singh et al. 2019), which can be divided into fossil fuel depletion and chemical element depletion. The chemicals used in the advanced treatment and sludge treatment were the main influencing factors of abiotic depletion potential-elements, and coal-fired power generation was the main influencing factor of abiotic depletion potential-fossil. Overall, MBR performed the worst in these two environmental categories and SBR performed the best.

(2) Acidification potential

For the four technologies, acidification potential was found to be 18.160-29.975 kg SO_2 eq. The contribution of electricity to acidification was more than 67%, mainly due to the emission of sulfur dioxide and nitrogen oxides during thermal power generation. The high energy consumption led to a higher acidification potential ~~value~~ for MBR than the other three technologies.

(3) Eutrophication potential

Eutrophication potential is considered to be one of the most important impacts of sewage treatment. Although the treatment system can greatly reduce wastewater pollutants, the residual nutrients such as total nitrogen and total phosphorus can still cause eutrophication potential. Fig.4 illustrates that effluent discharge provided the main contribution to eutrophication, accounting for 83%-97% of the four technologies. It is believed that effluent discharge from sewage treatment plants is one of the major reasons for global eutrophication (Renou et al. 2008). In addition, indirect emissions from the chemical production process might also lead to eutrophication. Compared with other technologies, SBR had the highest eutrophication potential (73.325 kg phosphate eq.), which can be decreased by enhancing the removal of nitrogen and phosphorus or by reducing the discharge of sewage through tail water reuse.

(4) Global warming potential

Global warming potential was mainly attributable to greenhouse gases (carbon dioxide, methane, etc.) emitted during the sewage treatment. As shown in Fig.2, MBR performed the worst in global warming potential, followed by OD, AAO and SBR. Fig.4 implies that the key processes contributing to GWP were sludge incineration treatment and electricity production. Due to the high demand for electricity (0.62 kWh/m^3 sewage) and more sludge (0.49 t/m^3 sewage, with 80% water content) generated in the actual production process, the MBR technology had the highest greenhouse effect. Therefore, it is necessary to save energy and reduce consumption in the process of sewage treatment, and pay attention to pollutant control in the process of sludge incineration.

(5) Ozone layer depletion potential

Ozone layer depletion potential means that the release of substances such as fluorine and chlorine groups leads to a reduction in the thickness of the ozone layer, thereby endangering the ecosystem and human health. The ozone layer depletion potential for the four technologies was around 3×10^{-13} kg R11 equivalent, which is the smallest among all environmental categories. The main contribution process was the consumption of electricity and chemicals, accounting for more than 90%. And the key impact substance was methyl chloride.

(6) Photochemical ozone creation potential

Photochemical ozone creation potential refers to the reaction of reactive hydrocarbons, nitrogen oxides and carbon monoxide to form photo-oxidized substances (i.e. ozone), which in turn affect human health. The electricity consumption of secondary treatment was the main process leading to photochemical ozone creation potential. Overall, MBR had the largest photochemical ozone creation potential, up to 2.525 kg Ethene eq.

(7) Toxicity potential

The toxicity potential mainly depends on the heavy metals emitted into the environment and can be divided into freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity and human toxicity potential. Indirect metal emission from electricity production was the main cause of TP, which is in agreement with previous studies (Piao et al. 2016; Singh et al. 2019). In addition, the use of chemicals and the disposal of sludge also contributed to the toxicity potential.

Electricity and chemicals contributed the most to freshwater aquatic ecotoxicity potential, with a contribution of more than 70% in the secondary treatment and sludge treatment phases. SBR owned the largest freshwater aquatic ecotoxicity (119.644 kg DCB eq.), mainly due to the release of vanadium (V), beryllium (Be), nickel and chrysene into water and air.

Compared with other environmental impact categories, marine aquatic ecotoxicity potential had the largest normalized value in sewage treatment, which is consistent with the researches by Kalbar et al. (2014) and Tong et al. (2013). As shown in Fig.5, more than 80% of marine aquatic ecotoxicity was derived from the pollution of hydrogen fluoride, beryllium and vanadium. Through the process contribution analysis, it is confirmed that about 90% of the contribution came from electricity production and solid waste treatment. Due to the large electricity consumption and sludge production, MBR had the greatest impact on marine aquatic ecotoxicity.

Concerning terrestrial ecotoxicity potential, it mainly occurred in two phases of sludge treatment and secondary treatment, which has a great relationship with the consumption of electricity and chemicals, accounting for more than 90%. Chromium, mercury, arsenic and vanadium were major contributors.

Human toxicity potential is mainly due to the release of heavy metals into water, air and soil (Kamble et al. 2019). Among the four scenarios, MBR had the greatest impact on human toxicity, while AAO had the least. The contribution of secondary treatment to HTP was 48-74%. Taking MBR as an example, 89% of human toxicity potential came from electricity consumption, followed by chemical consumption (9%). The key substances were arsenic and nickel, which account for 24% and 41%

respectively.

3.3. LCC analysis

Existing studies had evidenced that the expenditure of operation phase is an important part of the cost of the sewage treatment process. Lorenzo-Toja et al. (2016b) and Lorenzo-Toja et al. (2016a) founded that construction phase only contributed 4% to the costs of urban water treatments. According to Su et al. (2019), the expenditure of electricity and chemical consumption is an important part of operating costs in the sewage treatment process. Innocenzi et al. (2020) reported that the chemical purchase necessary for the treatment was the major component of the total cost for the treatment of wastewater. Xue et al. (2019) founded that apart from operation phrase, the rest of the stages contributed to less than 8% of the total cost of wastewater treatment. Besides, according to previous studies, only LCA and LCC have the same scope and basic assumption, LCC can effectively supplement the analysis of LCA results to achieve sustainability assessments (Di Maria et al. 2020; Hoogmartens et al. 2014). Therefore, LCC considered the operation stage from sewage pumping into the plant to final discharge. From the contribution analysis of Section 3.2, it is known that electricity and chemical consumption in operation phases were major contributors to most of environmental impact categories.Considering that pollution discharge fees in China are based on local unified standards, they are generally linked to discharge volume and have nothing to do with the processes adopted by the sewage treatment plant. Therefore, only the cost of electricity and various chemicals was accounted for LCC, accompanied by the joint analysis of the corresponding environmental impact. Fig.6 integrates the economic and environmental indicators of the four sewage treatment technologies. The total economic costs of the four technologies were 3398, 5650, 4416, and 4524 yuan respectively. Combined with the normalized overall LCIA results, MBR had the largest economic cost and environmental impact. AAO performed best and could be regarded as an optimal technology from both economic and environmental perspectives.

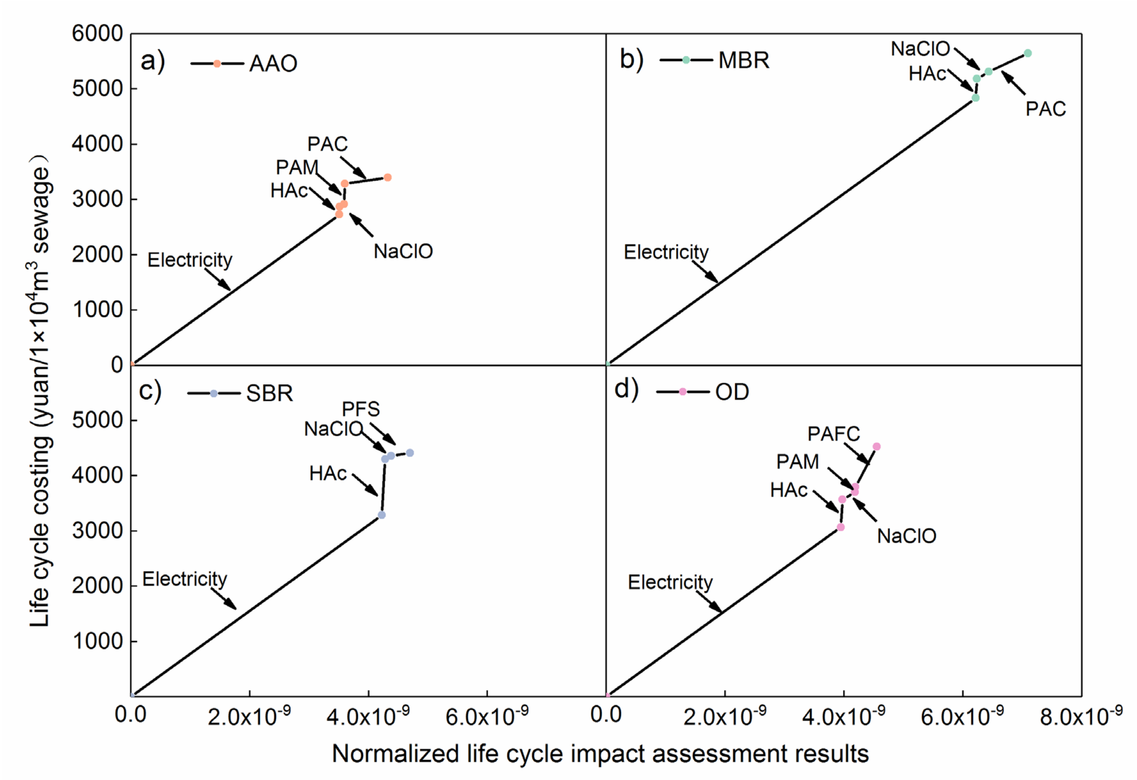


Fig.6. Life cycle economic versus environmental impact. PAC: poly aluminum chloride; PAFC: poly aluminum ferric chloride; PFS: poly ferric sulfate; PAM: polyacrylamide.

As shown in Fig.6, electricity presented a very high economic and environmental burden, accounting for 67% and 81% respectively. In addition, flocculants such as poly aluminum chloride (PAC) and poly aluminum ferric chloride (PAFC) also had a certain economic and environmental burden. This is similar to the discovery that flocculants had an important impact on the digestive treatment of pig manure (Duan et al., 2020). As a carbon source additive, acetic acid (HAc) had a high economic cost (4.13%-22.94%), but the corresponding environmental impact was relatively small (0.12%-1.2%). Generally speaking, it is necessary to improve the efficiency of energy usage, optimize the chemical production process, as well as reduce the consumption of electricity and chemicals, which can effectively reduce the environmental impact and economic load, so as to achieve a win-win situation.

3.4. Sensitivity analysis

Based on the joint analysis of LCA and LCC, the consumption of electricity and main chemicals (flocculants) in sewage treatment were selected with a 10% variation for sensitivity analysis. The corresponding life cycle environmental and economic impact changes are shown in Table 3.

The results show that electricity consumption was the most sensitive process. Changes in electricity usually bring maximum environmental and economic benefits, similar to previous studies (Li et al. 2019). When the electricity consumption was reduced by 10%, the overall LCIA results of four sewage treatment technologies were decreased by more than 6%. Five environmental impact categories, such as abiotic depletion potential-fossil, acidification, human toxicity, marine aquatic ecotoxicity and photochemical ozone creation potential, were greatly affected by electricity changes. Among them, human toxicity potential had the largest variability (8.21%-8.86%). It should be noted that the reduction in electricity had the least environmental benefits for eutrophication and abiotic depletion potential-elements. At the same time, the electricity changes also had a greater impact on the economic cost, with a sensitivity of 6.79%-8.56%.

Compared with electricity consumption, flocculants contributed less to reducing the overall environmental impact and economic costs. The sensitivity of flocculant consumption to economic impact is less than 2%. Because of the high price of PAFS, the economic sensitivity of the OD scheme was up to 1.61%. Flocculant consumption has a certain contribution to the environmental impact of AAO, in which abiotic depletion potential-elements and ozone layer depletion potential show a high sensitivity of about 5%. However, for MBR and SBR schemes, environmental and economic indicators were less sensitive (less than 1%).

According to the sensitivity analysis, it is of great significance to decrease the consumption of electricity and flocculants during the operation stage of the sewage treatment. In practical terms, as discharge standards become more and more stringent, wastewater treatment is often based on the cost of a substantial increase in energy and chemical consumption. The pursuit of self-sufficiency in energy consumption is in line with the concept of sustainable sewage treatment, such as sludge incineration for power generation, while heat recovery is often neglected. Treated wastewater has great thermal energy potential (Hao et al. 2019; Guo et al. 2019), and the heat recovered on-site by heat pump technology can be used for sludge drying and other heating in the plant. Developing more environmentally friendly flocculants to replace traditional chemicals such as PAC is also a new direction to be considered in the current sewage treatment. In addition, the environmental impact of sewage treatment can be significantly improved by optimizing the power structure and adopting low-energy equipment. By comparing different power schemes, Li et al. (2013) and Polruang et al. (2018) have proved that most environmental impact categories could be improved by using renewable energy such as wind power, hydropower, etc.

Table 3 Sensitivity analysis of main contributors with a 10% variation.

Category	AAO		MBR		SBR		OD	
	Electricity	PAC	Electricity	PAC	Electricity	PFS	Electricity	PAFC
ADPE	0.42%	5.64%	0.48%	3.25%	0.91%	0.0041%	0.35%	1.82%
ADPF	5.81%	2.89%	6.84%	1.75%	7.48%	0.01%	6.20%	1.20%
AP	6.73%	1.49%	7.22%	0.83%	7.91%	0.01%	7.19%	0.62%
EP	0.17%	1.27%	0.27%	1.07%	0.15%	0.0002%	0.16%	0.47%
FAETP	7.72%	1.72%	8.54%	0.98%	2.84%	6.99%	6.50%	2.77%
GWP	3.31%	1.31%	4.22%	0.86%	5.04%	0.0052%	2.79%	0.43%
HTP	8.21%	1.40%	8.86%	0.78%	8.36%	1.28%	8.56%	0.75%
MAETP	6.74%	1.22%	7.53%	0.70%	8.23%	0.27%	6.44%	0.48%
ODP	3.45%	4.52%	4.13%	2.79%	6.16%	0.04%	3.53%	1.81%
POCP	7.09%	1.62%	8.14%	0.96%	8.77%	0.10%	7.37%	0.67%
TETP	7.61%	1.58%	8.46%	0.90%	2.15%	7.71%	5.78%	3.32%
LCA	6.32%	1.30%	7.21%	0.76%	7.30%	0.55%	6.06%	0.55%
LCC	8.04%	0.33%	8.56%	0.60%	7.44%	0.12%	6.79%	1.61%

4. Conclusions

In this paper, LCA and LCC were integrated to quantitatively analyze the environmental and economic impacts of four typical sewage treatment technologies in China, including AAO, MBR, SBR and OD. The results show that AAO was the optimal treatment scheme. The main processes responsible for the environmental and economic burden were the consumption of electricity and chemicals. Overall, electricity consumption was the biggest hot issue. Reducing energy consumption can bring relatively high benefits. It is also recommended to increase more environmentally friendly flocculants, tail water reuse and incineration end control to reduce the impact on water and atmospheric environment.

On the whole, LCA and LCC can be used as good environmental and economic evaluation tools for system assessment. This study is helpful for managers to build up a better understanding of four typical sewage treatment technologies in China from both economic and environmental aspects. Through identifying important contributions and hot issues during the life cycle, the findings provide insight into the potential impacts caused by various aspects of the process, thereby supporting decision-making. In addition, considering that the evaluation results are affected by various aspects such as system boundary and influent wastewater quality, the next study can be further improved to supplement the Chinese sewage treatment database.

Declarations

- **Ethics approval and consent to participate**

Not applicable.

- **Consent for publication**

Not applicable.

- **Availability of data and materials**

All data generated or analyzed during this study are included in this published article and its supplementary information files.

- **Competing interests**

The authors declare no conflict of interest.

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- **Authors' contributions**

Hui Jiang: Methodology, Software, Formal analysis, Investigation, Data curation, Writing-Original Draft. **Qiang Jin**: Conceptualization, Investigation, Supervision. **Panpan Cheng**: Software, Validation, Writing-Review. **Ming Hua**: Project administration. **Zhen Ye**: Writing-Review & Editing.

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Appendix A. Supplementary data

Supplementary data related to this article can be found online at .

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