Original Research Paper | doi https://doi.org/10.46488/NEPT.2021.v20i05.027 | **Open Access Journal**

Comparative Life Cycle Assessment Analysis of Sewage Sludge Recycling Systems in China

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ABSTRACT

With the acceleration of economic development and urbanization in China, sewage sludge generation has sharply increased. To maximize energy regeneration and resource recovery, it is crucial to analyze the environmental impact and sustainability of different sewage sludge recycling systems based on life cycle assessment. This study analyzed four sewage sludge recycling systems in China through life cycle assessment using the ReCipe method, namely aerobic composting, anaerobic digestion and biomass utilization, incineration, and heat utilization and using for building materials. In particular, the key pollution processes and pollutants in sewage sludge recycling systems were analyzed. The results demonstrated that aerobic composting is the most environmentally optimal scenario for reducing emissions and energy consumption. The lowest environmental impact and operating costs were achieved by making bricks and using them as building materials; this was the optimal scenario for sludge treatment and recycling. In contrast, incineration and heat utilization had the highest impact on health and marine toxicity. Anaerobic digestion and biomass utilization had the highest impact on climate change, terrestrial acidification, photochemical oxidant formation, and particulate matter formation. In the future, policy designers should prioritize building material creation for sludge treatment and recycling.

INTRODUCTION

With the rapid development of the economy and urbanization in China, municipal sewage has gradually become a huge environmental problem that needs to be urgently solved. To maintain ecological sustainability, the improvement of wastewater treatment focuses on saving energy and resources, recovering nutrients, and reducing waste production (Linderholm et al. 2012). Sewage sludge, as the main solid waste after wastewater treatment, increases with an increase in sewage treatment volume annually. Sewage sludge disposal and management have become an inescapable problem after wastewater treatment. In wastewater treatment systems, the "heavy sewage light sludge" phenomenon is common, and the environmental impact of wastewater cannot be entirely eliminated.

Sludge generation in China steadily rose annually from 11 million tons in 2005 to 21 million tons in 2010, with sludge having 80% water content. The dry sludge production in China is summarized in Fig. 1; it showed an average annual growth of 9% from 2011 to 2017. Sewage sludge treatment has previously been considered secondary to wastewater treatment but is gradually becoming one of the most significant challenges facing municipal wastewater management worldwide, particularly in China (Yang et al. 2015). Currently, the main methods include aerobic sludge fermentation for

agricultural waste, anaerobic digestion to recover biomass, incineration, or production of building materials or fuel (Mininni et al. 2015, Hong et al. 2009, Zhang et al. 2017). In fact, the large quantity of sewage sludge should not be considered a heavy burden to municipal management but rather a great source of bioenergy and recovered material (Raheem et al. 2018, Tyagi & Lo 2013).

Life cycle assessment (LCA) is a technique used to assess the environmental impacts associated with all stages of a product's life from raw material extraction through material processing, manufacturing, distribution, use, repair and maintenance, and disposal or recycling (Ekvall et al. 2017, ISO 2006, Pasqualino et al. 2009). At present, LCA, as a management evaluation to analyze the environmental impact, is used for technical comparison of certain methods of sludge treatment to identify technological improvement in the further (Huppes & Oers 2011, Kelessidisa & Stasinakis 2012, Scheutz 2018, Schrijvers et al. 2016, Suh & Rousseaux 2002, Xiao et al. 2018, Xu et al. 2014). Simultaneously, the environmental impact of different sludge treatment methods is evaluated by LCA, especially greenhouse gas emissions and energy efficiency (Houillon et al. 2005, Li et al. 2017, Li & Feng 2018, Liu et al. 2011, Mill et al. 2014, Li & Feng 2018). Yoshida et al. (2018) reviewed 35 published studies
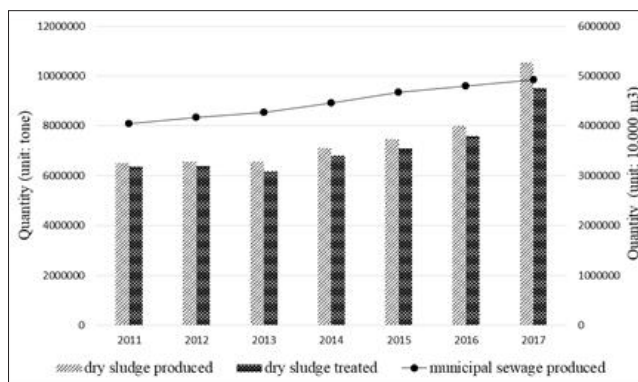
Fig. 1: Dry sludge produced, dry sludge treated, and municipal sewage produced in China

on life cycle assessment (LCA) of sewage sludge for their methodological and technological assumptions. Overall, LCA has been providing a flexible framework to quantify the environmental impacts of wastewater and sewage sludge treatment and disposal processes for multiple scales, ranging from process selection to policy evaluation. The results of LCA are, in principle, unique to the goal and scope of each study, reflecting its local conditions, and comparison between different LCAs is not intended. Furthermore, the assessments are limited by the methodological development of the life cycle impact assessment (LCIA) and the advancement of research in quantifying environmental emissions associated with wastewater and sewage sludge treatment processes. With the significant impact of global warming, accurate calculation of greenhouse gas (GHG) emissions is essential, including direct emissions and indirect emissions (Ding et al. 2021). The direct emissions of GHGs are incomplete in environmental impact assessments (EIAs), which unaccounted for direct CO_2 emissions.

Furthermore, Hospido et al. (2010) evaluated the reuse of anaerobically digested sludge in agriculture from an environmental point and specifically quantified the potential impacts of emerging micropollutants such as pharmaceuticals (Hospido et al. 2010, Xu et al. 2014). In a later comparative study, Heimersson et al. (2017) identified and explored several scenarios to handle multi-functionality in the LCA of a sludge handling system (Ekvall et al. 2007, Heimersson et al. 2017). The authors used LCA to examine the environmental impact of strategic sludge treatment and end-use decisions. The authors also modeled resource recovery and accounted for different possibilities for secondary functions such as biogas and sludge used in agriculture. In contrast, Linderholm et al. (2012) investigated the environmental impact of sewage sludge as a phosphorus alternative for agriculture. Their study focused on secondary functions, such as nutrient input to soil (Johansson et al. 2008, Linderholm et al. 2012).

In the case of comparative "Waste LCAs", as the amount of waste treated can be equal in the different scenarios, a simplification is done by excluding the upstream materials and processes from the system boundaries. This means that the system is focused only on waste treatment. This concept is called the "zero burden assumption" and is also known as the cut-off approach. This "zero burden assumption" concept was first used on an LCA system simplification for a comparative "Waste LCA" analysis (Huppes & Oers 2011, Piao et al. 2016). While some of these technologies exist only at laboratory or pilot scales, others are fully functional at the industrial scale, and there is a growing willingness to increase the sustainability of sludge management via recovery processes that extract potentially marketable value-added products. In this study, sewage sludge was considered "waste"—free of environmental impact—where the sewage sludge recycling process was designed to produce a product with high added value in the recycling system (Pradel et al. 2016). This created uncertainty in the comparative LCA of the system that produced the value-added products used by sewage sludge. The limitations of this study include incomplete accounting of GHG emissions and uncertainty caused by ignoring the environmental impact of sewage sludge.

The aim of this study was to identify the environmental and economic impacts of four sewage-sludge recycling systems to determine the optimal system in China. This research contributes to the field by evaluating the sustainability of sludge management based on the recovery and reuse of potential value-added products and modeling the sludge as waste to assess the environmental impact of sludge treatment. Moreover, the main environmental impacts and corresponding pollution phases of the four systems were identified as suggestions for technology or management improvements in the future.

MATERIALS AND METHODS

Goal and Scope

The goal of this study was to compare and assess four sewage sludge recycling systems from an environmental and economic viewpoint, to obtain clear results about the environmental preferences of both viewpoints to enable decision-makers to develop a sustainable sewage sludge disposal policy. The LCA of scenarios was performed from a 'gate to gate' perspective and comprises all environmentally relevant processes from sludge as waste to the finished energy recovery or material substitution. The functional unit of this LCA was 1 ton of sewage sludge, including 80% moisture.

System Boundary

The boundary of Scenario 1 (S1), the incineration process using fluidized bed combustion technology, includes partial drying of sludge to achieve 40% dry matter content using the heat of the incineration of flue gases, incineration of sludge, heat and electricity generation, and exhaust gas purification. Aerobic composting (Scenario 2 (S2)) using high-temperature fermentation includes mixing with conditions and fermentation bacteria to achieve a 60% moisture rate, primary fermentation to reduce the moisture rate to 50%, and secondary fermentation to obtain a fertilizer substitute and purify exhaust gas. Scenario 3 (S3) proposed the use of sewage sludge as a raw material substitute in brick production, including mixing with other raw materials; the brick-making process, including making bricks, drying bricks, and roasting bricks; exhaust gas purification, and brick production. Scenario 4 (S4), which was the anaerobic digestion process in an AAe anaerobic digestion reactor that

reacts at high solid concentration, includes conditioning with reflux sludge, anaerobic digestion, biogas, and heat generation, and exhaust gas purification. The overall scope of this study, comprising the most important processing stages involved in sewage sludge treatment and recycling and included in LCA, is shown in Fig. 2.

Life-Cycle Inventory

This study was based on data from both sewage sludge treatment processes. Thus, the processes of the four scenarios are based on the EIA of each sludge disposal plant. The difference in sludge composition used in the four scenarios is not taken into account in this study to compare four different methods. The significant variations in data are attributed to the waste-water treatment plants in China because they do not send proper reports on the treatment and final disposal of their sewage sludge. To carry out the inventory, data was mainly collected from EIAs for projects using four sludge treatment technologies and from the Chinese Life Cycle Database (CLCD). The overall inputs and outputs to be measured in the study should be elementary flows. To evaluate the function of sludge treatment and recycling systems, a large amount of basic data is necessary. Energy and raw material use, as well as emissions from energy production activities such as electricity generation, are among them.

The use of sludge and other solid waste will not exacerbate the intensity of consumption of natural resources; hence, the analysis of inventory data only considers the energy consumption and pollutant emissions of raw materials, such as crude and iron, in the process. First, we established the energy-material balance for each unit process based on the function of the unit. Then, we created the inventories for each
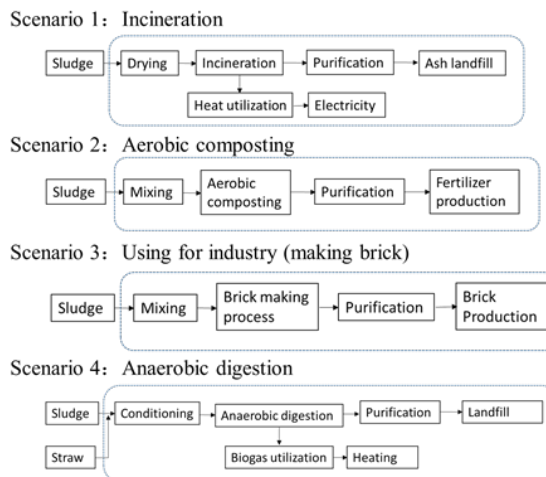

Fig. 2: System boundaries of the cradle-to-gate for both energy recovery or material substitution scenarios using treated urban sewage sludge.

scenario based on the functioning of units in each scenario shown in Table 1. The life cycle inventory of the scenarios includes the following aspects (Wang et al. 2015):

1) Main technical indicators of scenarios, including production and specifications;

2) Consumption of various raw materials in the scenarios, including the use of waste;

3) Energy consumption;

4) Water consumption;

5) The amount of pollutants contained in the ecology system;

6) The amount of pollutants produced by conventional production was reduced by sludge recycling.

RESULTS AND DISCUSSION

To analyze the outstanding environmental impact category and evaluate the environmental impact of each scenario, the normalization results, as presented in Table 2, were calculated using the world reference values and characterization results. Using the midpoint environmental impact weights,

we calculated the endpoint environmental impact; the results showed that the endpoint environmental impact was S2 < S4 < S1 < S3.

An environmental load of each scenario on different environmental impact categories was analyzed based on the characterization results. As the impact of S2 for every environmental category was significantly lower than that of the other three scenarios, the characterization results of S1, S3, and S4 were compared and analyzed. The environmental load of S1 in TT was significantly higher than that of the other two scenarios. In terms of CC, AP, MEP, HT, FT, MT, POFP, and PMFP, the environmental load of S4 was the most obvious of the three scenarios. Climate change, human toxicity, photochemical oxidant formation, particulate matter formation, and ozone depletion were the impact categories that affect human health. S2 had a positive value for each of these categories. S4 should focus on the environmental impact categories of CC, HT, POFP, and PMFP. S1 had a significant impact on each category, especially ozone depletion.

Paying attention to the greenhouse gas emissions during the sludge disposal process can reduce other pollutants caused by energy consumption, and alternatively, it can

Table 1: Inventory of main energy and materials consumption of the four scenarios.

Inventory flow	Unit	S1	S2	S3	S4	Inventory flow	Unit	S1	S2	S3	S4
Input											
Electricity	kWh	108.18	-73.413	1.09	294.81	Crude	kg	-0.14	-	24.552	-
Gas	kg	20.60	-		-	Water	kg	33.70	1305	72.5	1.9
Coal	kg	-5.57	-10.2	65.2	-0.546	Iron	kg	-	-	-8.23E-06	-
Output											
NH_3	kg	0.01	-12.75		0.01	As	kg	-2E-05	-3.28E-02	-	-
H_2S	kg	4E-04	0.03	5E-04	0.02	Cr	kg	-1.62E-06	-8.28E-03	-	-
HCl	kg	0.01	-	0.007	-	Ni	kg	-2.3E-05	-1.23E-05	-	-
HF	kg	0.002	-0.017	0.007	-	V	kg	-2.76E-05	-1.42E-04	-	-
SO_2	kg	0.105	-1	0.41	-0.002	Zn	kg	-2.3E-05	-1.42E-04	-	-
CH_4	kg	-0.025	-0.128	-	-0.005	Dioxin	kg	2E-08	-	-	-
NMVOC	kg	-0.0047	-0.024	-	-	COD_{cr}	kg	1.4	0.049	0.03	2.3
CO	kg	0.025	-0.437	-	-	NH_3-N	kg	0.14	-4.047	0.003	2
CO_2	kg	139.728	-654	-2.85E-05	-0.947	CxHy	kg	-	-0.075	-	-
NO_x	kg	0.548	-0.99	0.29	0.0183	SO_4^{2-}	kg	-	-0.025	-	-
Dust	kg	38.47	5.55	1	-0.15	N_2O	kg	-	-1.656		-
Hg	kg	8.92E-05	-4.32E-06	-	-	NOx-N	kg	-	-0.166		-
Cd	kg	8.99E-05	-8.64E-04	-	-	TN	kg	-	-	-	2.7
Pb	kg	1.83E-04	-3.88E-03	-	-	TP	kg	-	-	-	0.3

Table 2: ReCiPe midpoint normalization results for all scenarios (Values are presented per functional unit).

Categories	Unit	S1	S2	S3	S4
Climate change [CC]	p/yr	4.94E-03	-1.53E-01	6.96E-04	7.41E-05
Terrestrial acidification [AP]	p/yr	5.18E-03	-2.03E+00	4.37E-02	1.26E-04
Marine Eutrophication [MEP]	p/yr	2.25E-03	-3.83E-01	5.58E-03	7.24E-04
Human toxicity [HT]	p/yr	1.70E-02	-3.31E+01	3.28E-03	3.69E-04
Terrestrial toxicity [TT]	p/yr	2.34E-03	-7.78E-02	1.34E-04	1.56E-05
Freshwater toxicity [FT]	p/yr	9.67E-05	-2.87E-02	2.48E-05	2.89E-06
Marine toxicity [MT]	p/yr	2.06E-02	-2.48E+00	2.74E-03	3.19E-04
Photochemical oxidant formation [POFP]	p/yr	2.40E-03	-9.05E-02	1.70E-02	4.52E-05
Particulate matter formation [PMFP]	p/yr	2.04E-02	-3.81E-01	2.37E-01	5.93E-04
Water depletion [WDP]	p/yr	1.21E-03	6.51E-03	7.12E-02	8.03E-07
Fossil fuel depletion [FDP]	p/yr	2.50E-03	-4.39E-02	3.20E-02	3.97E-05
Freshwater eutrophication [FEP]	p/yr	0	-1.32E+01	0	1.27E-03
Metal depletion [MDP]	p/yr	0	0	-3.84E-07	0
Ozone depletion [ODP]	p/yr	2.05E-04	0	6.55E-03	0

motivate people to develop new clean energy technology. Therefore, climate change is an impact category that is specifically considered in research.

Fig. 3 presents the relative constituents of the impact on the climate change category. From the results of the climate change impact, S2 had a positive environmental impact. The reason for the positive environmental impact of S2 was the reduction in N_2O. N_2O is produced in mineral fertilizer production, and it has a huge influence on climate change. N_2O was not significantly generated in S2 compared with
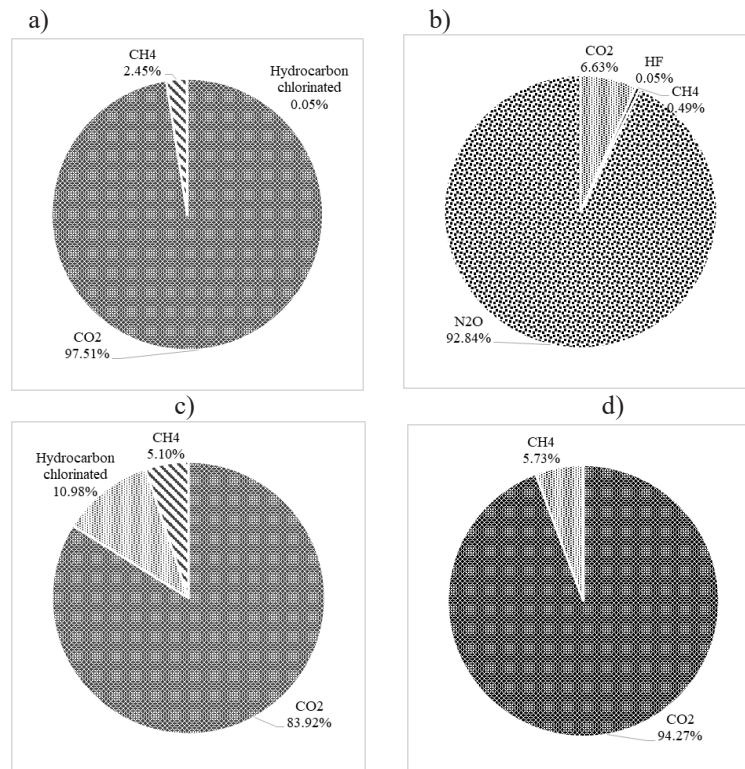

Fig. 3: The relative constituents about the impact category of climate change a) scenario 1, b) scenario 2, c) scenario 3, d) scenario 4.

mineral fertilizer production. According to the analysis of the contributors to climate change, the main pollutant driving climate change is CO_2. Organic matter content and energy utilization are the main sources of CO_2. Therefore, the organic matter content in the sludge should be reduced. Additionally, sludge treatment and recycling should focus on energy conservation.

Fig. 4. shows the proportion of each environmental impact category in the four scenarios. S2 presents an obvious positive environmental impact. In addition to certain environmental impacts in WDP, S2 was beneficial to the environment in other impact categories. From the normalization results (Fig. 4), the most obvious midpoint environmental impact category was human toxicity, followed by freshwater eutrophication, marine toxicity, and terrestrial acidification.

The main normalization results of different processes in S2, as shown in Fig. 5, were reflected in the reduction of

environmental load by replacing the mineral fertilizer. The most obvious midpoint environmental impact category of S2 was HT and FEP. Heavy metals, such as As, Cd, Pb, and Cr, are produced during mineral fertilizer production. As a result, heavy metal resources are derived solely from indirect emissions caused by energy use. The environmental impact of human toxicity in S2 was significantly reduced, showing an overall impact on the environment.

These normalization results indicated the relative magnitude of the environmental impacts of aerobic composting on sludge-based fertilizer production compared to mineral fertilizer manufacture at a global level. In the midpoint environmental impact categories of human toxicity and freshwater eutrophication, there were impacts that were significantly beneficial to the environment, and the environmental impact was also relatively reduced in terms of marine toxicity and terrestrial acidification. During the entire life cycle of the
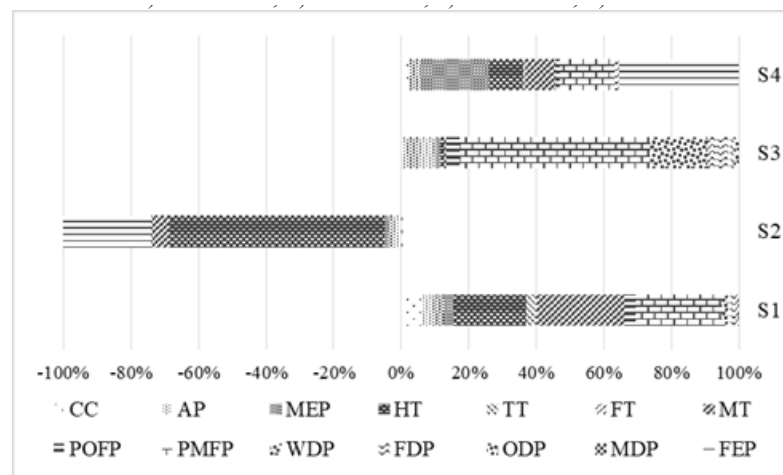

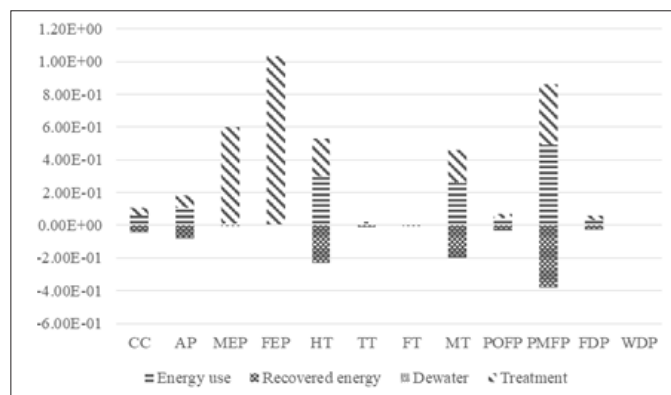Fig. 4: The proportion of each impact category in four scenarios.

Fig. 5: The normalization results of aerobic composting (S2) as well as the offset caused by material substitution.

mineral fertilizer production process, the stages included ore extraction, transportation, energy consumption, and mineral fertilizer production. In S2, sewage sludge—considered "waste"—was free of any environmental burden when used for sludge-based fertilizer production. Therefore, the production of sludge-based fertilizers instead of mineral fertilizers should be promoted in the fertilizer industry.

The environmental impacts of the other three sludge treatment and recycling systems were mainly from energy consumption and sludge treatment and recycling processes, and the environmental impacts during the pretreatment process were negligible.

From the perspective of environmental assessments, S3 had the greatest number of negative environmental impacts of the four sludge treatments and recycling systems. According to the normalization results shown in Fig. 6, PMFP and WDP had significant negative environmental impacts during S3, which was 4-200 times that of other environmental impact

categories such as CC. Dust, SO_2, and NOx lead to particulate matter formation during the treatment process of S3. The process of making bricks causes water depletion.

On the other hand, FDP, AP, and POFP also showed obvious environmental impacts. The main sources of FDP, AP, and POFP, which are shown in Fig. 7, are treatment processes including SO2, CO, CH4, non-methane volatile organic compounds (NMVOC), NOx, HF, HCl, and dust. They are derived from emissions during the production of raw materials and the brick-making process. POFP and PMFP are the major midpoint environmental impact categories affecting human health in S3. According to the analysis of the released constituents (Fig. 7), NOx (87.77%) and SO2 (10.07%) were the principal sources of PMFP. In addition, dust (87.24%) was the principal source of POFP. Therefore, in S3, the sludge treatment and recycling process should improve the production technology to reduce water use and carry out clean production to reduce the environmental im-
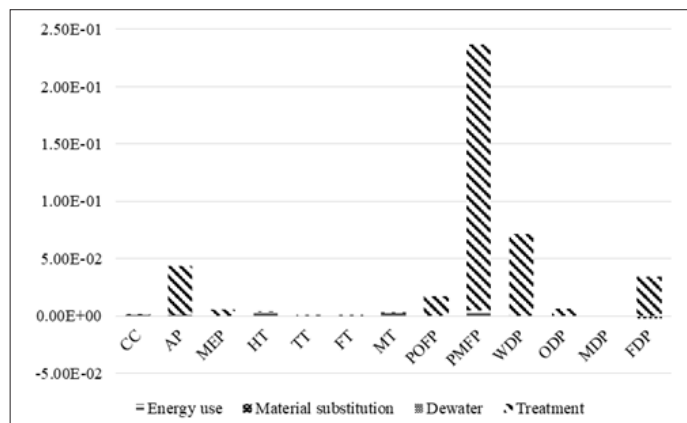

Fig. 6: The normalization results of using in industry (S3) as well as the offset caused by material substitution.

a)

b)

Fig. 7: The relative constituents about midpoint environmental impact of human health in Scenario 3
a) PMFP, b) POFP.

pact of the treatment process. According to the normalization results of S1 shown in Fig. 8, HT, MT, FDP, and PMFP are obvious impact categories in which S1 has the most serious environmental impact.

In the environmental impact categories of CC, AP, and FDP, S1 also had significant negative environmental impacts. CC, HT, and PMFP were the major midpoint environmental impact categories of human health in S1. Fig. 9 presents the relative constituents of each environmental impact category. From the perspective of CC, the environmental impact mainly comes from the use of fossil energy and the emission of CO_2 (98%) during sludge incineration. The main sources of human toxicity were heavy metals, hydrocarbons, and dioxins, of which Cr (53.89%) and Hg (32.91%) are the main influences. Cr is mainly derived from energy consumption and Hg is in the process of sludge incineration. However, the mechanism of dioxin production is complicated. For example, dioxin is easily produced when the incineration temperature is less than 800°C during the burning of domestic garbage. Among them, PMFP pollutants

come from dust (81.39%) during energy consumption and incineration.

Therefore, according to the above analysis, energy consumption is the main cause of HT, MT, POMF, AP, and CC. In S1, pollutants were mainly derived from energy consumption, and heavy metal and dust emissions were high because China still relies mainly on thermal power generation. Therefore, in future production processes, the use of clean energy should be gradually promoted to reduce the proportion of thermal power generation. At the same time, the incineration process should focus on the collection and treatment of dust in S1.

From the normalization results of S4 shown in Fig. 10, FEP, MEP, HT, MT, and PMFP were the most serious environmental impacts in the environmental impact categories, followed by AP, CC, POFP, and FDP. Among them, the environmental impact of TT, FT, and WDP was almost zero, and the impact of S4 on these environmental impact categories can be neglected.

The source of the FEP is the production of TP during anaerobic digestion. The main causes of MEP are NH_3-N
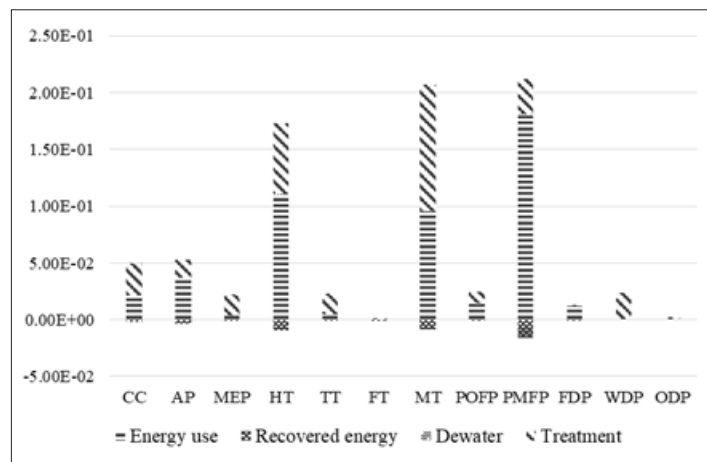

Fig. 8: The normalization results of incineration (S1) as well as the offset caused by recovered energy.
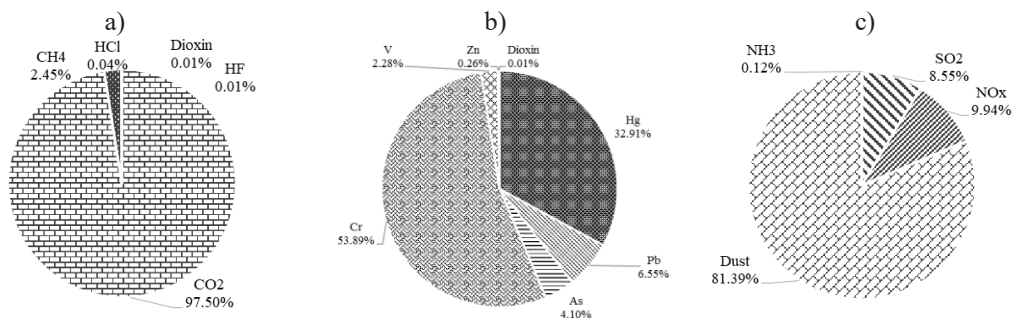

Fig. 9: The relative constituents about midpoint environmental impact of human health in S1
a) CC, b) HT, c) PMFP.

and TN, which are produced during anaerobic digestion, and NOx from energy production. CC, HT, PMFP, AP, and MT pollution sources are mainly derived from pollutants generated during and after energy production and use and are the most obvious midpoint environmental impact categories of human health in S1, followed by CC and POFP. The main constituent of HT was AS (87.94%), as shown in Fig. 11. The main reason for PMFP was PM10 (85.17%) during the process of energy production and consumption. The main influencing constituent of CC was CO_2 (94.27%),

similar to S1. TN (62.27%) and NH_3-N (35.98%) caused the impact of POFP during the energy consumption and treatment process of S4.

In view of this, the main pollution from S4 comes from heavy metals and dust in energy production and pollutants of N and P in the process of anaerobic digestion. Therefore, the utilization of clean energy should be promoted, and technology should be improved to reduce the pollutant emissions of N and P in the future. The other three scenarios, in addition to S2, had the greatest impact on the midpoint of particulate
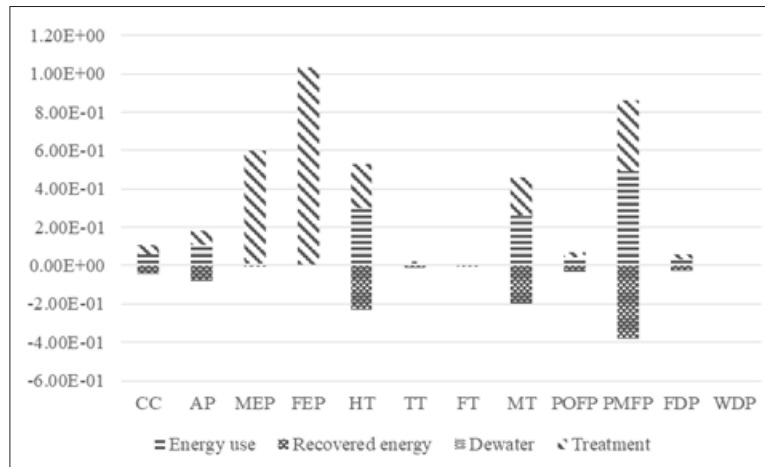

Fig. 10: The normalization results of anaerobic digestion (S4) as well as the offset caused by recovered energy.
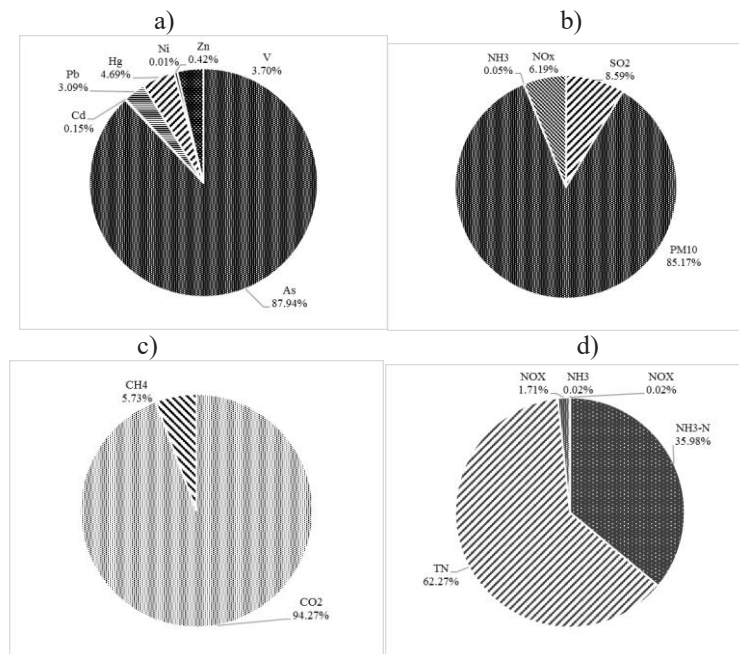

Fig. 11: The relative constituents about midpoint environmental impact of human health in scenario 4 a) HT, b) PMFP, c) CC, d) POFP

matter generation due to emissions from sludge treatment and recycling operations, as well as indirect emissions from energy use. Incineration and anaerobic digestion have obvious environmental impacts in the four midpoint environmental impact categories of global warming, human toxicity, marine toxicity, and fossil fuel depletion.

The operating costs of the sludge treatment and recycling system were estimated using the functional units of the four scenarios. China's subsidy policy for sludge recycling has not been well defined. In fact, each province has its own detailed subsidy policy. Jiangsu Province has a clear subsidy policy for the four scenarios involved in this study (Liu et al., 2013). Therefore, this study adopted Jiangsu's subsidy policy for sludge recycling. Based on the statistical results, the operating costs under the subsidies for each program are listed in Table 3.

The operating costs and the environmental and economic impacts of the various programs are basically the same. Combined with the environmental assessment results of the four schemes, S2 had the highest operating cost and the lowest environmental impact. Among the other three options, S3 had the least environmental impact and the lowest operating cost, as shown in Fig. 12, which is similar to the findings of Han et al. (2021). Compared with Liu et al. (2013), incineration was the optimal method, followed by anaerobic digestion and aerobic composting. The theoretical value of incineration and actual operation may have caused the differences in the results (Liu et al. 2013). In Xiao et al. (2018), hydrothermal-pyrolysis technology as a new method demonstrated the best performance with the lowest consumption of land resources, a relatively small environmental impact, and high economic benefits compared with other methods. The scenario of creating building materials (bricks) was not considered in Xu et al. (2014), and anaerobic digestion was a suitable alternative for sewage sludge treatment (Xu et al. 2014). In sum, it is similar to the comparison of the results obtained with previous literature.

CONCLUSION

This study shows which scenarios of sludge treatment and recycling systems are more sustainable during the period of operation from an environmental perspective. Human health is the primary impact category of the overall environmental impact. S2 was the most environmentally friendly scenario, with the fewest emissions and lowest energy consumption. S3 was the optimal scenario, based on the lowest environmental impact and operating costs. According to the analysis of pollutant sources and composition, treatment and recycling processes mainly account for the environmental impacts. According to the endpoint environmental impact results, human health was the primary endpoint environmental impact category for the scenarios. In the midpoint characterization results of human health, S1 had significantly higher environmental impacts on CC and HT than other scenarios, and S3 had obvious environmental impacts on POFP and PMFP.

In S1, pollutants were mainly derived from energy consumption, and heavy metal and dust emissions were high because China still relies mainly on thermal power gener-

Table 3: The cost under subsidy of four scenarios (Values are presented per functional unit).

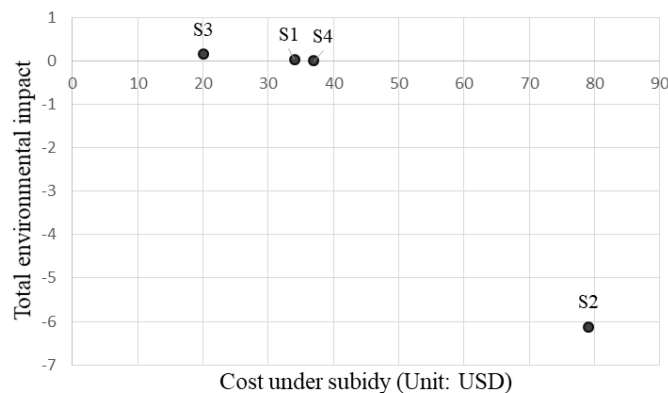|	S1	S2	S3	S4
Cost ($)	34	79	20	37

Fig. 12: Total environmental impact and operating cost of four scenarios.

ation. Therefore, in future production processes, the use of clean energy should be gradually promoted to reduce the proportion of thermal power generation. At the same time, the incineration process should focus on the collection and treatment of dust in S1.

Considering the environmental assessment results of the four schemes, S2 had the highest operating cost and the lowest environmental impact. The reason for the minimal environmental impact of S2 was that sewage sludge—considered "waste"—was free of any environmental burdens when used for sludge-based fertilizer production. In the future, the operating costs of S2 should be minimized. Therefore, the production of sludge-based fertilizers instead of mineral fertilizers should be promoted in the fertilizer industry.

In view of the above analysis, S3 was the optimal solution among the four scenarios because of its minimal operating costs and relatively small environmental impact. When comparing the human health impact, PMFP, POFP, and ODP were major impact categories. The treatment process was the main source of these environmental impacts. The treatment plants should carry out clean production to reduce dust and nitrogen oxides during the treatment process.

S4 should focus on CC, HT, POFP, and PMFP, which cause damage to human health. MEP and FEP are also obvious impact categories in S4. In view of the above analysis, the main pollution in S4 comes from heavy metals, NMVOC, and dust in energy production and pollutants of N and P in the process of anaerobic digestion. Therefore, the utilization of clean energy should be promoted, and the technology should be improved to reduce the environmental impact, especially pollutant emissions of N and P.

The following limitations of the study should be noted when considering the conclusions of the study. This study investigated the environmental performance of the systems investigated during their operation and does not consider the effect of their construction. Due to methodological issues with their classification and normalization, some impact categories, such as land occupation and the indirect effect of the avoided fertilizer on agricultural land application, were not considered. Finally, the data and assumptions used in this study were based on the Chinese context.

In future research, life cycle cost analysis will be added to the study, and the economic evaluation of the four programs will be considered more completely. Local factors such as economic level and industrial structures in various regions of China should be considered in future studies on the planning of sewage sludge reuse in various regions of China.

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