ENVIRONMENTAL LIFE CYCLE ASSESSMENT AND LIFE CYCLE COST ANALYSIS OF SEWAGE SLUDGE RECYCLING SYSTEM IN CHINA

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Sewage sludge is the solid waste produced in the biological treatment of wastewater. With the acceleration of the economy and urbanization in China, the generation of wastewater has increased sharply. Previous studies almost focused on environmental and economic performance, while comparative analysis integrated the environmental, economic, and social performance of the application to the potential resource recovery was ignored. Therefore, the following have been constructed in this study: (1) Environmental and economic performance of WAS reutilization method (i.e., sludge-to-electricity, fertilizer, building material, biogas) was evaluated under replacing the traditional and similar commodities on the market in full using life cycle assessment (LCA) and environmental life cycle costing (eLCC) with system expansion method. (2) Whole life costing (WLC) was represented the impact of pollutants on society, which applied to include externality cost which respects the monetization of emissions. Major pollutants that contributed to the externality cost of those systems were identified. The net present value of each WAS reutilization system was comparing which helps to guide technology improvement and government decisions. LCA results indicate the method of sludge-to-fertilizer and sludge-to-building material outperform other methods while the third and fifth year achieve breaking even, showed by eLCC result. Only scenario 2 has sustainable development via WLC analysis, but the break-even year has exceeded 5 years, which had lost its market competitiveness.

Then, the sewage sludge reutilization management system under low environmental-economic-social performance was proposed which provides sewage sludge reutilization reference for government and industries. Consequently, the future perspectives of sludge reutilization in China and suggestions on sustainable sludge recycling management for developing countries were deduced.

Key Words : *Wastewater activated sludge, Recycling management, Life cycle assessment, Life cycle cost, Externality costs*

1. INTRODUCTION

With the acceleration of the economic development and urbanization in China, the amount of wastewater activated sludge (WAS) reached 39.04 million tons (80% moisture content) in 2019, and approximately 50% had not been properly treated[19]. Sludge disposal is considered a problem in wastewater treatment plants and municipal waste management. However, in the philosophy of "circular economy," WAS is considered a renewable resource with high levels of organic matter and nutrients[27]. Various energy forms and productions can be generated from WASR system[10) 11)], such as electricity[26) 4)], biogas[26) 4)], fertilizer[22) 21)], and building materials[24) 1)]. Meanwhile, WAS treatment and disposal management in China lack a scientific plan that simultaneously considers environmental pollution reduction, economic feasibility, and social adaptability. Hence, deriving a reliable and comprehensive assessment method based on overall performance is crucial.

In previous studies, life cycle assessment (LCA) and life cycle cost (LCC) are widely used to evaluate environmental and economic impacts in sludge management schemes[18) 23) 6) 16) 25)]. Liu et al. (2013) evaluated the greenhouse gas performance and LCC of six sludge treatment scenarios for the Tai Lake watershed in China: landfill, mono-incineration, co-incineration, brick manufacturing, cement manufacturing, and fertilizer for urban greening. Rostami et al. (2020) compared the environmental impact and LCC of incineration, landfill, and composting and concluded that composting is the most environmentally and economically friendly method in Mashhad. Hong et al. (2009) assessed the environmental and economic performance of six sludge treatment scenarios in Japan. Both LCA and LCC have been used worldwide to compare different sludge treatment options. However, the integrated environmental and economic impacts of the WASR system considering alternative production have rarely been discussed.

To fill this assessment gap and meet the practical requirement, we applied whole life costing (WLC) as defined in BSI ISO 15686–5 (2008) to combine the two aspects by adding the externality cost, representing the monetized value of environmental pollutants.

Therefore, this study aims to integrate environmental and economic evaluation models of six WASR systems in China via LCA and LCC methods and proposes future optimization scenarios. The main contribution of pollutants to externality costs that mark potential social damages caused by pollutant discharge for WASR management are also determined.

2. METHODOLOGY

(1) Goal and scope definition

This study aimed to assess the environmental and economic performance of four WAS treatment and recycling technologies and to compare them with different policy scenarios. The function unit processed 1 t of WAS with 80% moisture content. The system included transportation, drying, pretreatment, production, and air pollution control treatment. Final products (i.e., electricity, fertilizer, brick, biogas, and fertilizer) generated from the WASR process were considered to replace traditional and similar commodities in the market (Fig.1). To avoid the allocation of any by-products in the process, system expansion was applied.

(2) Data source and life cycle inventory

Life cycle inventories for incineration, aerobic composting, the production of bricks, and anaerobic digestion were collected from enterprises via environmental impact assessment (EIA) report. Life cycle inventories of replaced main products were based on the Chinese Life Cycle Database and previous studies [20) 2) 7) 17)]. The socio-economic circumstances, efficiency of each technology, and quality of WAS may significantly affect environmental and economic performance. Therefore, each WAS from wastewater plants needs to be evaluated on a case-by-case basis[16)]. To perform a comparative study, we assumed

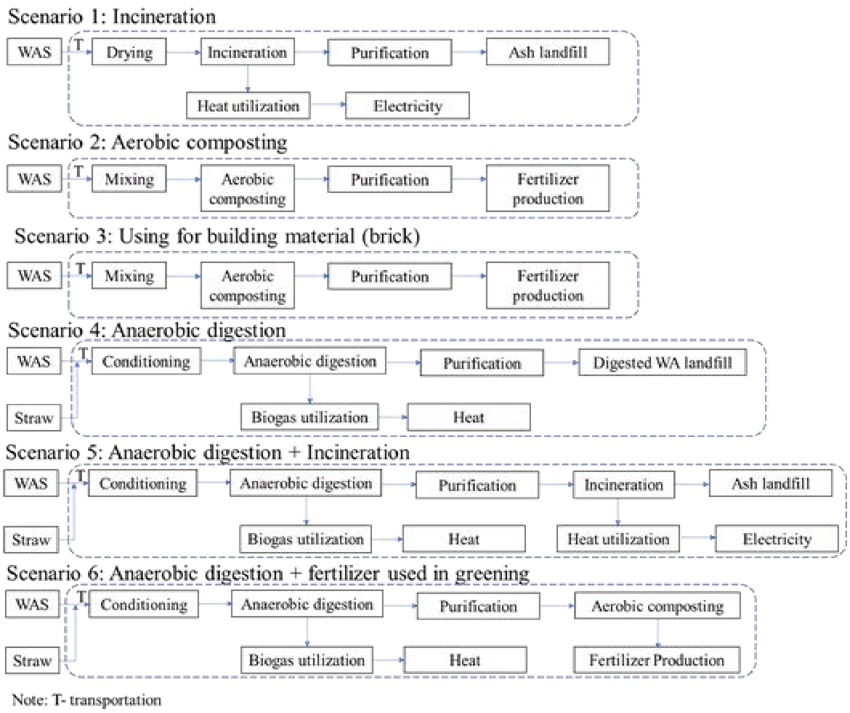


Fig.1 System boundaries of six scenarios of WASR system.

that the quality of WAS complies with the standard GB 24188-2009 and that quality changes and differences in regions do not significantly influence the evaluation results in this study.

Economic data on budget costs were from market investigations and EIA reports of each enterprise. Operation costs in this study included transportation, raw material, energy consumption, and labor costs. The sale incomes represent all incomes from final product sales. Final product and raw material prices were obtained from the public domain reflecting their market price in 2019. WAS disposal subsidy lacks a standard for each city in China; hence, this study referred to the subsidy in Chongqing (205 CNY/t). The transportation distance between each technology was assumed to be 100 km.

The externality cost based on the valuation method in Japan could not be applied to China due to different economic development stages and environmental thought levels[13]. However, the externality costs was based on the Environmental Protection Law in China and CREO 2017, respectively. For missing data of externality cost, the reference of monetization value of per unit total emissions was from a previous study[20].

(2) Environmental and economic evaluation

In this study, the environmental performance of WASR was evaluated and quantified using LCA by ReCipe 2008[16) 5)]. It was the preferred methodology due to the wide range of potential environmental effects it covers, such as climate change (CC, kg CO2 eq), terrestrial acidification (TA, kg SO2 eq), marine eutrophication (MEP, kg N eq), freshwater eutrophication (FEP, kg P eq), human toxicity (HT, kg 1,4-DB eq), terrestrial toxicity (TT, kg 1,4-DB eq), freshwater toxicity (FT, kg 1,4-DB eq), marine toxicity (MT, kg 1,4-DB eq), photochemical oxidant formant (POFP, kg NMVOC eq), particulate matter formation (PMFP, kg PM10 eq), water depletion (WDP, m3), fossil fuel depletion (FDP, kg oil eq), and ozone depletion (ODP, kg CFC-11 eq). It was the preferred methodology due to the wide range of potential environmental effects it covers[9]. The total environmental performance (EP_{total}) represented the EP of each category indicated for the WASR system. The avoided environmental performance (EP_{avoid}) represented the EP from products replacing the same number of traditional products. EP_{net} represented the "true environmental performance" of each scenario, calculated by Eq (1) as follows:

$$EP_{net} = EP_{total} - EP_{avoid} \qquad (1)$$

To present the LCA results more concisely and eliminate the temporal and spatial influence, EP_{total} and EP_{avoid} were normalized according to the characterization result of each system based on the global normalization values with the average weighting set, and the missing value of WDP was set according to the China Water Resources Bulletin in 2016.

LCC was classified into three types: conventional-LCC (cLCC), environmental-LCC (eLCC), and societal-LCC[13]. In terms of the eLCC of each WASR system, LCC was undertaken and indicated by net present value (NPV), as shown in Eq (2a). The CI_i was the sum of cash inflow in the year i, such as the WAS subsidy and final product incomes of each system. The CO_i was the sum of cash outflow in the year i, such as capital cost, operational cost, and taxes. If the NPV of the fifth year is greater than zero, the WASR system presented commercial feasibility with higher NPV in view of market experiences in China[25]. Break-even year represented the first year, wherein cash inflow is greater than cash outflow (NPV>0).

$$NPV_i = \sum_{i=0}^{n} (C_{Ii} - C_{Oi})(1 + 10\%)^{-i} \qquad (2a)$$

$$Externality\ cost_j = \sum_{j=0}^{6} t_j \cdot \sum_{j,k} e_{j,k} \cdot P_k \qquad (2b)$$

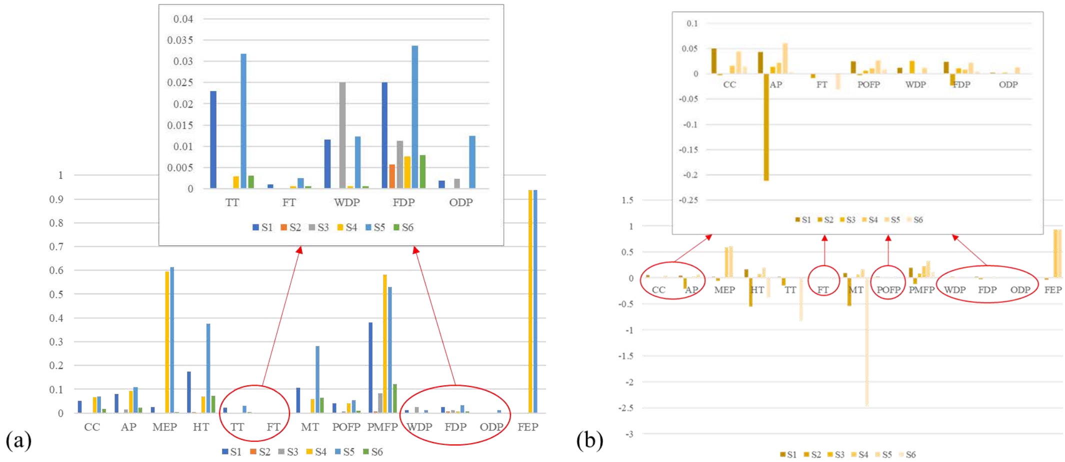
WLC included eLCC and externality cost to merge the comparative performance, and presented "true cost" of each scenario was applied according to BSI ISO 15,686–5. The externality cost of each scenario was estimated by Eq (2b) using the Ecotax 2002 method in Sweden[12) 3)]. It resulted from multiplying the amount of emission k ($e_{j,k}$) and per-unit price of emission k (P_k) for each scenario. The exchange rate used in this study was 1 USD=6.804 RMB.

The total externality cost of each scenario was classified into four groups, such as water quality, human health, climate change, and indeterminate[14) 12)]. The monetized value of total nitrite, total phosphate, NH_3-N, and heavy metal emitted to water contributed to the externality cost of water quality. The externality cost of climate change included the monetized value of CO_2 and CH_4. The monetized value of heavy metals and other air emissions, made up the human health contribution to externality cost.

3. RESULTS AND DISCUSSION

(1) Environmental performance

According to the results of EIA reports and previous studies, 1 ton of WAS with 80% moisture rate and digested WAS (30% moisture rate) were burned to generate 9.6 and 855.8 kWh, respectively. For scenarios 2 and 5, fertilizer produced by 1 ton of WAS or digested WAS could replace 7.86 kg of fertilizer used in agriculture (N%, 5%) or 6.7 kg fertilizer used in gardening (N%, 3%). Briefly, 41.6 m^3 biogas could be generated by anaerobic digestion using 1 ton of WAS. Furthermore, 1 ton of WAS replaced clay as raw material and could generate 351 tons of bricks. In Fig. 2, the highest EP_{total} except WDP is observed scenario 6 exhibited the lowest EPnet in six scenarios. In contrast, scenario 5 exhibited the highest EPnet except for CC, TT, WDP, and FDP. Scenarios 3, 4, and 5 exhibited the highest EP_{net} in WDP and FEP categories. CC, TT, and FDP categories for scenario 1 exhibited the highest EP_{net}. Therefore, scenario 2 was sustainable in environmental performance, and



Note: CC: kg CO2 eq, TA: kg SO2 eq, MEP: kg N eq, FEP: kg P eq, HT, kg 1,4-DB eq, TT: kg 1,4-DB eq, FT: kg 1,4-DB eq, MT: kg 1,4-DB eq, POFP: kg NMVOC eq, PMFP: kg PM10 eq, WDP: m3, FDP: kg oil eq, ODP: kg CFC-11 eq)

Fig.2 eLCC assessment result of each scenario for WASR system.

(a) EP_{avoid}; (b) EP_{net}

for scenario 5 ascribed to the largest consumption of electricity and auxiliary fuel during AD and drying before incineration. However, EP_{total} of scenario 2 was the least because the energy consumption, electricity, and fossil fuel, were less than those of other scenarios. Compared with scenario 4, scenario 5 and scenario 6 had incineration and composting steps after WAS digesting, thereby consuming more energy and discharging more air pollutants. The consumption of fossil fuel was the main reason for EP_{total} in scenario 3, and CH_4 contributed indirectly to electricity consumption in all scenarios. EP_{avoid} in scenario 2 was the highest because the toxicity of heavy metals in producing fertilizer using chemical raw materials was more than that produced with the same nitrogen content of the WAS recycling fertilizer. Scenarios 1 and 3 were the lowest in EP_{avoid}. For scenario 1, a large amount of energy consumption during the drying process led to a lower EP_{avoid}. EP_{avoid} of scenario 3, wherein WAS replaced 10% clay, was lower than the others because energy consumption and pollutants were not decreased. Overall, EP_{net} of scenario 2 exhibited the lowest environmental impact in 10 environmental categories apart from TT, FT, and MT. In the environmental category of TT, FT, and MT, the sustainability of scenario 5 was questionable and needs further demonstration.

(2) Economic performance

a) eLCC assessment

The break-even years of scenarios 3 and 4 presented favorable market expectations in the third and fifth years, respectively. Scenarios 1, 2, and 6 individually became NPV-positive in 10, 8, and 14 years, respectively. The economic performance of scenario

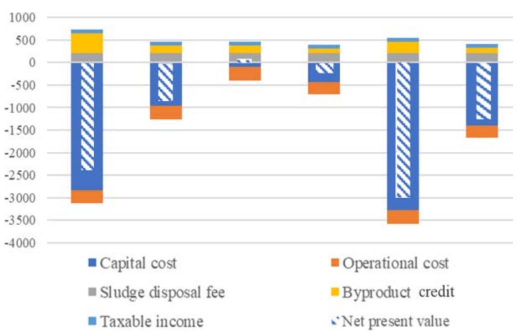


Fig.3 NPV1 of six WASR scenarios by eLCC method.

3 was the best due to the lowest investment cost compared with other scenarios, with the lowest sales income. Although sales income of biogas and electricity in scenario 5 were the highest, the break-even year was over 30 years owing to the highest investment cost with a new plant. Hence, the break-even year of scenario 5 was reduced with the existing incineration plant to recycle electricity, which has not been studied so far. Expect for scenario 3, the capital investment cost covered over 40% in NPV for other scenarios.

The key operational cost, which was transportation cost, was further analyzed to provide suggestions for improvement, as shown in Fig.3. Result demonstrate that transportation cost covered over 56% in operation costs. Therefore, the location of reutilization and transportation path optimization can be rationally mapped out in future WASR management. For scenarios 2 and 3, the water cost was the major contributor apart from transportation cost, wherein the increasing moisture rate of WAS when leaving wastewater treatment plants must be considered. Transportation and water costs should be balanced in future management because the volume was relative to the moisture rate of WAS, and transportation cost increased with the volume of WAS. For other scenarios, the energy costs, such as electricity, natural gas, and coal, were major contributors in addition to transportation costs, and their economic performances can gain profit from improving energy efficiency.

Table 1 NPV of six scenarios from WLC perspective. (unit: CNY)

	NPV1	NPV5	NPV10
Scenario 1	-2773.534	-2666.429	-141.0947
Scenario 2	-833.0569	-330.2881	190.87583
Scenario 3	-87.94048	-73.82782	-141.0947
Scenario 4	-684.024	-1745.617	-3289.903
Scenario 5	-3611.693	-5033.024	-7040.922
Scenario 6	-1648.903	-2635.569	-3870.293

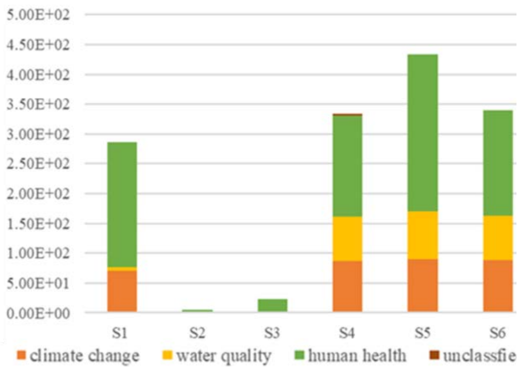


Fig.4 Contribution of environmental emissions to externality costs. (unit: CNY)

b) WLC assessment

The most influential category of externality cost in all scenarios was human health, as shown in Fig.4. For human health, SO_2 and NO_x were the major contributors, and ammonium polluted into water was the biggest contributor for water quality. Approximately 95% of the external cost of human health in scenario 4 originated from SO_2, NO_x, and Hg. The main pollutants affecting human health in scenarios 1, 5, and 6 were the same as in scenario 4. In addition to SO_2 and NO_x in scenarios 2 and 3, NH_3 was the main pollutant. The external costs of scenario 5 were twice that of other scenarios presented in Fig 3, and the external costs of scenarios 2 and 3 were significantly lower than the other scenarios.

According to the WLC results (Table 1), only scenario 2 had a sustainable development, and the break-even year exceeded 5 years, wherein it had lost its market competitiveness. However, the non-uniform accounting method of external costs may lead to changes in the results of WLC[15]; therefore, this study does not consider the impact of the method on the evaluation results.

4. SUMMARY

Based on the results, scenarios 2 and 3 are the preferred schemes for WAS recycling. However, according to the national standard, considering the accumulation of heavy metals in WAS in agricultural products, the fertilizers produced in scenario 2 are currently used for agricultural quantity and time constraints. We suggest that heavy metals in WAS should be controlled in the future, and municipal sewage and industrial sewage should be treated separately. From the perspective of WLC, scenario 3 is superior to other solutions and has market potential. However, product quality needs more control, because the heavy metals in WAS are transferred to the product. As of 2019, 27% of the sludge is treated by incineration. If scenario 3 completely replaces scenario 1, it will reduce greenhouse gas emissions by 99% of CO_2 eq, and the total cost will be reduced by 75%. The environmental and economic analyses results of scenarios 1, 5, and 6 do not support its industrialization potential. We suggest that we consider co-processing the existing incineration plant and fertilizer plant rather than constructing a new plant to reduce the initial capital investment. For scenario 4, we recommend extending the industrial chain and using digested sludge to continue producing higher value-added and more environment-friendly main products, such as those from scenarios 5 and 6[26].

There are uncertainties and limitations in this study. For example, the EIA of the company lacks statistics on CO_2 currently in China. Therefore, future research should focus on evaluating the WASR system combined with other factors (different transportation radius, different regional characteristics, different WAS composition, and market demand for WAS products) to achieve overall environmental friendliness, economic feasibility, and flexibility of WASR.

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