Environmental impact and economic benefit evaluation of sewage sludge treatment technologies

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Abstract. In order to evaluate the environmental and economic performance of continuous thermal hydrolysis (CTH) of sludge disposal, we compare the CTH with three traditional technologies including anaerobic digestion, aerobic composting and dry-incineration. This study uses life cycle assessment (LCA) to assess their environmental impact of the above technologies, and selects ten characteristic indicators from e-Balance analysis software for quantification. We also adopt the cost-benefit ratio (B/C) to evaluate the technologies’ economic performances, and come to conclusion that the larger the value is, the more economically feasible it will be. The results show that, as a new sludge disposal technology, CTH has the best performance in both environmental and economic aspects, while dry-incineration and anaerobic digestion have the worst results in environmental and economic aspect respectively. Although sludge compost has a moderating effect on global warming, it could also be potentially toxic. Nevertheless, the use of raw materials and energy contributes significantly to the environmental impact of each scheme.

1. Introduction
Sewage sludge (SS) contains many toxic substances, such as pathogens, heavy metals and organic pollutants. Sludge disposal is a very complicated and challenging task, if not properly handled will cause serious environmental pollution[1]. Many sludge treatment and disposal technologies have been widely used. At present, sludge composting mainly refers to aerobic composting, which can improve the maturity of sludge and the byproducts are used as green soil or forest fertilizer for sludge stabilization.[2]. Sludge incineration was first applied in the field of harmless sludge treatment. The formation and control of dioxins is an important restriction factor for the spread of sludge incineration technology. Sludge anaerobic digestion can kill most pathogens in sludge to achieve the goal of harmless sludge[3]. In recent years, thermal hydrolysis of sludge has been widely concerned. Neyens et al. confirmed that the alkaline and acidic hydrolysis of sludge was effective in reducing residual sludge volume and improving water dewatering[4]. Choi et al. optimized thermal hydrolysis pretreatment of sewage sludge to enhance anaerobic digestion, and the results showed that it could effectively enhance methane production and decrease rate of volatile solids[5].

This paper presents an emerging continuous thermal hydrolysis (CTH), which has been as a municipal sludge treatment project in Liaoning province operation for a year. Although it is technically feasible, it has not been a detailed assessment of the environmental and economic performance. In order to highlight its advantages better, we need to use some tools to predict the overall environmental burden[6].

Life cycle assessment (LCA) is one of the commonly used methods to analyze the environmental impact of production or service processes and can be applied to sewage sludge management systems to
assess their overall environmental burden[7]. In the early research, Suh et al. compared the environmental impact of five alternative treatment schemes of sewage sludge in France, but land occupancy and avoiding the indirect effects of fertilizer on agricultural land were not counted[8]. Li explored several sludge treatment technologies in terms of environmental impact, energy efficiency and economic performance in the past two years, and obtained the best performance process[9],[10].

The purpose of this study is to evaluate the environmental and economic performance of CTH and compare it with three traditional sludge treatment technologies including anaerobic digestion, aerobic composting and drying incineration. To accomplish this task, the LCA approach is used in order to consider the whole process of sewage sludge treatment. This includes their resource consumption, pollutant emissions and their associated environmental impacts to facilitate decision makers to evaluate and screen each program throughout the entire process.

2. Method

2.1. Goal and scope definition

The study follows the ISO14044(2006) standard procedure, which defines the LCA approach as four phases, namely goal and scope definition, inventory analysis, impact assessment and result interpretation. E-balance[13], a general life cycle assessment and analysis software with independent intellectual property rights, is carried out to make the life cycle environmental impact assessment for four processes in this paper.

2.1.1. Functional unit. One ton of dry solids (DS) is defined as the functional unit for calculation and comparison.

2.1.2. System boundary. This study considers only the operational phase, not the construction and abolition phases, and its potential impact was negligible in the long run[15]. Minor resource costs, such as human resources for office buildings and office supplies and monitoring and testing instruments, are ignored, and it is generally accepted that their contribution to the life cycle inventory is negligible[16]. In order to facilitate comparison, the calculation process of LCA starts from the concentrated sludge with a water content of 97% (TS content of 3%) to the end of the final stabilization treatment. The concentration mode is gravity concentration, and the system boundary is shown in figure 1.

![Figure 1. System boundary.](image-url)
2.2. Inventory analysis
Life cycle inventory includes resource consumption, pollutant emissions and by-products. S1 is an anaerobic digestion process with thermal hydrolysis pretreatment and data derive from references [17] and [18]. The data of S2 are from on-the-spot investigation. The energy consumption and emission data of S3 are obtained from references [19], [20], and [11]. In S4, the material consumption of drying co-incineration includes auxiliary fuel alkaline reagent and water. The sludge dry solid transport to coal-fired power plants for incineration power generation and specific data are from the reference [21]. Due to the lack of production data for the upstream process, polyacrylamide (PAM) emission factors are calculated based on acrylonitrile production capacity. We select 10t heavy duty diesel truck for transportation and the transportation distance is assumed to be 30 km. Since sludge is considered a biological source, CO₂ emissions from sludge treatment are omitted from the inventory.

3. Results and discussion

3.1. Evaluation methodology
In this study, ten characterization indicators including CML2001, CML2002, ISCP2010, IPCC2007 and IMPACT2002+ are integrated: land use (LU), primary energy depletion (PED), malodours air (MA), eutrophication potential (EP), acidification potential (AP), global warming potential (GWP), terrestrial ecotoxicity (TAETP), marine ecotoxicity (MAETP), freshwater aquatic ecotoxicity (FAETP), and human toxicity potential (HTP).

3.2. Characterization and Dimensionless results

3.2.1. The characterization results of four scenarios

| Category | Unit          | S1       | S2       | S3       | S4       |
|----------|---------------|----------|----------|----------|----------|
| LU       | m² a          | 5.02E-02 | 4.39E-02 | 1.03E-01 | 1.19E-01 |
| PED      | MJ            | 1.18E+04 | 1.11E+04 | 4.90E+03 | 1.31E+04 |
| MA       | m³ air        | 1.02E+07 | 1.18E+07 | 1.27E+07 | 1.03E+07 |
| EP       | kg NO₂-Eq     | 6.66E-02 | 3.71E-02 | 2.32E-01 | 3.22E-01 |
| AP       | kg SO₂-Eq     | 2.14E+00 | 3.39E+00 | 1.13E+00 | 3.11E+00 |
| GWP      | kg CO₂-Eq     | 8.10E+02 | 8.47E+02 | 4.79E+02 | 8.94E+02 |
| TAETP    | kg 1,4-DCB-Eq | 2.93E-03 | 2.23E-04 | 8.09E-04 | 1.98E-03 |
| MAETP    | kg 1,4-DCB-Eq | 3.13E+00 | 1.86E+00 | 5.61E+00 | 2.93E+00 |
| FAETP    | kg 1,4-DCB-Eq | 2.58E+00 | 4.52E+00 | 1.92E+01 | 4.52E+00 |
| HTP      | kg 1,4-DCB-Eq | 1.27E+02 | 2.94E+01 | 1.84E+02 | 1.09E+02 |

3.2.2. Dimensionless results. We divide the environmental impact values of the four scenarios in table 1 by the maximum values of the corresponding categories, and get the dimensionless result of 10 indicators. The total environmental impact result of the four scenarios is S4>S3>S1>S2 and the details are shown in figure 2. It illustrates the most favorable and unfavorable effects of four scenarios in 10 categories. And the larger their values are, the worse the scenario will be for the environment in this category. S1 has a higher influence on TAETP and GWP categories but performs well in EP, LU, and FAETP. S2 performs better in several toxic impact categories, but has higher GWP and AP. S3 has maximum values in the four environmental impact categories, including MA, MAETP, FAETP, and HTP, but its lowest value is PED. S4 had the worst overall performance and only performed better in FAETP category.
3.3. The cumulative contribution of four scenarios

The (a), (b), (c) and (d) in Figure 3 demonstrate the process contribution of four scenarios respectively.

As shown in (a) of Figure 3, thermal hydrolysis in the EP, AETP and HTP category contribution is significant because the thermal hydrolysis consumes large amounts of electricity and heat. In (b), thermal hydrolysis and thickening process exhibit the worst results due to the use of electricity, steam and agents in both processes. In (c), owing to the limitation of sludge composting on the moisture content
of sludge, a lot of PAM will be used in the process of sludge dehydration, which will lead to a vital influence on the air and human. Moreover, the transportation cost of composting is high, because the sludge still has a large weight after dehydration. As shown in (d), the use of coal and auxiliary fuels in the co-incineration process contributes the most to the environmental impact. Due to the lack of upstream production data of the by-products of S2, LCA calculation cannot be carried out. Therefore, the avoided environmental impacts of four scenarios are converted into economic benefits for evaluation.

3.4 Economic benefits analysis.

According to[17], S1 produces 125.77Nm$^3$ methane, which can generate power of 314.4kWh and the grid-connected price is calculated at 0.75 yuan/kWh. The hydrolysate produced by S2 is 0.55t with fulvic acid content of 250 g/L, and the average market price is 2000 yuan per ton, with a total revenue of 1100 yuan. Sludge composting can be used as soil improver, but the market recognition is very low[23]. The compost products in this paper are nitrogen fertilizer and phosphate fertilizer, with an average price of 580 yuan/ton, and the economic benefit is 255.2 yuan/t DS. The cost data of S3 and S4 are from[24]. An operation of sludge drying incineration project was investigated. It is calculated that the power recovery capacity of sludge co-incineration was about 600kWh/t DS, which is consistent with the research results[25]. The economic benefit is 450 yuan/t DS based on the S1 grid price. To make economic comparisons between the four scenarios, we use the benefit-cost ratio (B/C) to represent the economic tradeoffs. When B>C, it means that economically feasible. Table 2 indicates that S2 shows the best economic performance and S1 is the worst. The final economic benefit ranking is S2>S3>S4>S1.

| Scenarios | Benefits(B) | Costs(C) | B/C  |
|----------|------------|---------|------|
| S1       | 235.8      | 1058.3  | 0.22 |
| S2       | 1100       | 750     | 1.47 |
| S3       | 255.2      | 350     | 0.73 |
| S4       | 450        | 1625    | 0.28 |

4. Conclusion

This study assessed the environmental impact and economic benefits of four sludge management scenarios. CTH is an emerging sludge disposal technology that has been applied in the actual operation of sludge disposal project; and show its best behaviour of environmental and economic evaluation in this paper. The findings of this study could help decision makers select the best sludge management options for sewage treatment plants or enterprises. The main conclusions are as follows:

- The sequence of environmental impact was: S2 < S1 < S3 < S4.
- The sequence of economic benefit was: S2 > S3 > S4 > S1.
- The costs of raw materials and electricity contributed an important part in all scenarios and the entire life cycle.

However, the sources of data other than those from field visits are uncertain. It is predictable that the traditional sludge management scheme will be gradually replaced, and sustainable sludge management schemes will dominate. Therefore, a systematic sustainability approach must be adopted in the future to evaluate CTH and provide decision makers with preferred sludge disposal options.

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