Environmental analysis of three wastewater treatment plants based on the life cycle assessment

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Abstract. Life cycle assessment (LCA) methodology was applied to examine the environmental effects of three wastewater treatment plants (WWTPs) with different size and processes located in northeast China. These WWTPs were assessed with acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), and human toxicity potential (HTP) as environmental impact categories. Among the processes the wastewater treatment line had the greatest environmental impact for all plants and impact categories due to the electricity consumption in the aerobic reactor. And the highest environmental impacts observed in the S-WWTP that operated by A2O process.

1. Introduction
Wastewater treatment plants (WWTPs) make significant contribution to the conservation for ecosystems in the surrounding aquatic environment by discharging wastewater effluents with lower concentrations of pollutants than those governed by the statutory water quality standard. On the other hand, a series of processes for wastewater treatment have direct environmental impacts, such as energy consumption, chemical reagents usage, significant sludge generation and other emissions. To minimize these environmental effects, Jorgelina et al. suggested a total wastewater treatment network system that could have more environmentally friendly impacts than distributed WWTPs [1]. Hoibye et al. proposed an approach to design the control structure and algorithms for optimizing the control of an integrated WWTP that could save the operation costs and fulfill the effluent discharge limits over a long period [2]. As a similar point of view, a life cycle assessment (LCA) is also a robust methodology for evaluating the current situation of the WWTP and proposing the best alternative for reducing the environmental impacts [3-6].

LCA is an assessment tool that systematically evaluates the potential environmental impacts of a system by quantifying a variety of input and output materials from the production of raw materials to the disposal of the waste generated [7-9]. In addition, it can allow the establishment of action plans for environmental improvements at all stages of production, use and disposal, and can present strategies by predicting the environmental load at the planning and designing stages [10-11]. The aim of this research is to analyse the environmental impacts of three WWTPs the LCA and to identify which treatment processes or the operational factors are causing a major environmental impacts such as acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), human toxicity potential (HTP).
2. Materials and methods

The environmental assessment method applied in this study was LCA. LCA is subject to the ISO 14040 evaluation standards, and can be divided largely into four steps[12-13] . The first step involves determining the goal and scope of the research, the target audience, and the data collection range. The quality of data has a significant influence on LCA results, and its reliability can only be guaranteed by pre-determining the data quality requirements, and then collecting the data and using them for the calculation. The second step is life cycle inventory (LCI), which requires the maximum amount of time in an LCA process. An accurate understanding of the production flow of the target product is essential for establishing a corresponding data list to enable effective data collection. Based on the data collected, an adequate research range should be determined according to the presence or absence of data and the existing data quality. In addition, the research range should be complemented repetitively. In the process of converting the collected data into the functional unit (FU), the LCA software is used to minimize the time required for manual operation; the Gabi Education Software version 5.0 was used in the present study [14]. The third step is life cycle impact analysis (LCIA), where the input/output data determined Step 2 (LCI) are classified based on the scope of the impact evaluation defined in Step 1, and impact analysis is then performed. The fourth step concerns an analysis of the results of Step 3 (LCIA), following by a sensitivity analysis of the LCA results to test their validity and reliability.

2.1. Goal and scope definition

The goal and scope definition includes the goal of the research, the target audience, as well as the data collection, system boundary and functional units, etc. This study considered three WWTPs located in northeast China. The three WWTPs were referred to as N-WWTP, S-WWTP, and G-WWTP. N-WWTP treats 150,000 m³/d of wastewater using a conventional activated sludge process. The sludge undergoes an anaerobic digestion process and the dewatered final sludge cakes were transported to a landfill site. The treatment capacity of S-WWTP was 780,000 m³/d, and it was operated using anaerobic/anoxic/oxic (A2O) process. The final dewatered sludge was transported to the composting site. For G-WWTP, the treatment capacity was 250,000 m³/d, and it treated using A2O-MBR (Membrane biological reactor) process. The sludge was treated by a dewatering process and then transported to landfill site.

In general, from a LCA point of view, LCA was conducted on all environment-associated factors throughout the relevant stages. All stages from the groundwork to the disposal are investigated with respect to energy consumption, natural resources depletion, waste treatment and disposal, and maintenance and management. The life time of a typical WWTP would be more than 50 years from its building to disposal. The infrastructure or dismantling of buildings or equipment was excluded from the scope of LCA since these two stages might not significantly influence the current operational state. Social impacts associated with odor emission and noise generation were also excluded from the analysis. In addition, sand and grit precipitating in the screen tank, which were the general waste of WWTPs with a relatively small daily quota of 0.2% of all the sludge produced, were excluded because of their negligible effect on the operational state.

The system boundary of the present study included all operation process stages between the influent, effluent and sludge, as well as all activities associated with them, such as wastewater treatment, sludge treatment, transport, landfill, and electricity and chemicals consumption. Because the three WWTPs chosen in this study were quite different in their size and influent composition, the three WWTPs LCA results were normalized to the functional unit (FU). The FU in this study was 1 m³ of influent wastewater. Figure.1 presents the system boundary.
2.2. Life cycle impact assessment

The life cycle impact assessment (LCIA) was carried out using the CML 2001-Nov.2010 method in the Gabi 5.0 Education software [14]. Each of the life cycle impact categories were calculated using Eq (1). The impact categories considered included AP (acidification potential, kg SO$_2$ eq.), EP (eutrophication potential, kg PO$_4$ eq.), GWP (global warming potential, kg CO$_2$ eq.), HTP (human toxicity potential, kg 1,4-DCB eq.) in this study.

\[ I_j = \sum I_{j,i} = \sum \left[ Q_{j,i} \times F_{j,i} \right] \]  

where \( I_j \) = indicator result of impact category \( j \)
\( I_{j,i} \) = indicator result of impact category \( i \) within impact category \( j \)
\( F_{j,i} \) = characterization factor for emission \( i \) within impact category \( j \)
\( Q_{j,i} \) = amount of emission \( i \) within impact category \( j \)

2.3. Life cycle interpretation

The interpretation in LCA was to assess the results in order to identify the inventory data that contribute to each environmental impact category and to determine the level of confidence in the final results. In this study, sensitivity analysis was conducted to determine the inventory data that affected the results most significantly. To confirm the LCA results, the data compared with published data that had been obtained from similar wastewater treatment process. Sensitivity analysis was conducted by changing the value of each inventory data by 10% of the raw values. The sensitivity value was calculated using the life cycle inventory data with Eq. (2).

\[ S_{j,i} = \left( \frac{\Delta I_j / I_j}{\Delta Q_{j,i} / Q_{j,i}} \right) \]  

where \( S_{j,i} \) = sensitivity of emission I within impact category \( j \).

3. Results and discussion

3.1. Life cycle impact assessment

In Table 1. showed the environmental impact of the four treatment processes in three WWTPs can be compared. The four treatment processes including wastewater line, sludge line, sludge transport, and
landfill. Among the wastewater treatment plants the highest environmental impacts in most indicators were observed in the G-WWTP. An analysis of the major causes led to the observation that N-WWTP and S-WWTP had reduced the electricity consumption during wastewater treatment because they used biogas-generated electricity. Among the wastewater treatment plants the highest environmental impacts in most indicators were observed in the S-WWTP (A2O process). In addition, large amounts of dewatered sludge generated in S-WWTP could have a significant effect on the environment of the final destination of the sludge.

Table 1. Environmental impact of four processes at the three WWTPs (functional unit: 1m³).

|                      | N-WWTP | S-WWTP | G-WWTP |
|----------------------|--------|--------|--------|
| Acidification Potential (AP) [kg SO₂-Equiv.] | 2.14E-04 | 3.56E-04 | 2.48E-04 |
| Eutrophication Potential (EP) [kg Phosphate-Equiv.] | 2.13E-05 | 3.54E-05 | 2.48E-05 |
| Global Warming Potential (GWP 100 years) [kg CO₂-Equiv.] | 1.65E-01 | 2.75E-01 | 1.89E-01 |
| Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.] | 4.87E-03 | 8.10E-03 | 5.58E-03 |

In Figure 2 the LCIA results were reorganized in terms of the proportional distribution of the 4 processes in each environmental impact category in the three WWTPs. Among the treatment processes, the wastewater treatment line had the greatest environmental impact, with a contribution of 35% to 72% for most of the indicators with the exception of the GWP. The highest impact for GWP was caused by the methane from landfill stage with a contribution of 55% to 65% in three WWTPs. Although wastewater lines discharge the CH₄ and N₂O from primary and secondary sedimentation tank and effluent, the CH₄ from landfill stage contributed more than five times GWP impacts. The environmental impact of the wastewater treatment line was caused mainly by the electricity consumption, which was originated from the aerobic reactor. 74% of electricity was consumed for wastewater treatment and 23% of that for sludge treatment.

About the AP, the electricity of wastewater line, electricity of sludge line, PAC consumption and landfill stages counted for 45%, 20%, 13%, and 13%, respectively in the G WWTP. In the other two WWTPs, the main contributions for the AP were similar to those of G-WWTP. The direct impact of the AP from the WWTP operation was relatively small compared to that from the background. In general, AP can be attributed to excess emissions such as H₂S, HCl, SO₂, NOx to air through the electricity production process. The SO₂ was emitted through the PAC production process and the SO₂ and NOx was emitted through the landfill stage.

About the EP, the impacts of the three WWTPs were almost identical. The main impacts were attributed to discharge of the treated effluent. More than 60% of the EP was contributed by the phosphate in the effluent. Besides, due to the ammonia and phosphorus emission to soil through the landfill process, the landfill process also occupied 22% in G-WWTP, 15.8% in S-WWTP, 14.2% in N-WWTP. The GWP in the S-WWTP and G-WWTP were remarkably higher than that in the N-WWTP.

The HTPs in the S-WWTP and G-WWTP were significantly higher than that in the N-WWTP. In the G-WWPT, the electricity for the wastewater and sludge treatment lines contributed more than 42% and 40% of HTPs respectively and about 17% of HTP was caused by landfill. In the S-WWTP 38% and 30% of the HTPs were caused by wastewater and sludge treatment line electricity.
3.2. Life cycle interpretation
The sensitive inventory components that could have a significant effect on the environmental indicators, where those effective components had sensitive values greater than 1. For the GWP in the N-WWTP, most sensitive item was the amount of dewatered sludge was the most sensitive item. Increasing the dewatered sludge data by 10% of the raw value would result in a 5.4% increase in the GWP of the N-WWTP. The most sensitive components for the EP were T-P whereas the most sensitive components for the AP and HTP were dewatered sludge and electricity, respectively.

4. Conclusion
This paper has presented a life cycle assessment of three different WWTPs in the northeast China. The processes in those plants were included the wastewater treatment line, sludge treatment line, transport, and landfill. The environmental impact was assessed in terms of the acidification potential, eutrophication potential, global warming potential, and human toxicity potential. The results of LCIA were showed that the wastewater treatment line had the greatest environmental impact, with a contribution of 35% to 72% for most of the indicators with the exception of the GWP. Among the processes the wastewater treatment line had greatest environmental impact with the major source being the electricity consumption in the aerobic reactor. This study demonstrated that the LCA methodology can be useful for evaluating environmental impacts occurred by the WWTPs in regional basis.

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