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Engaging multiple weighting approaches and Conjoint Analysis to extend results acceptance of life cycle assessment in biological wastewater treatment technologies

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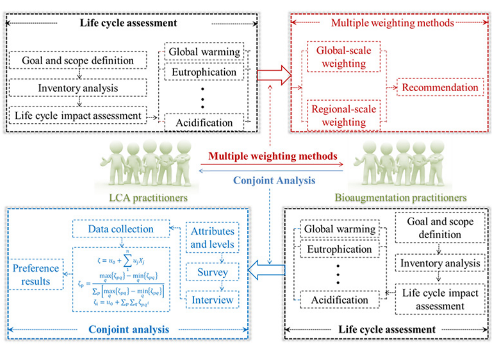
GRAPHICAL ABSTRACT



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ABSTRACT

Environmental impacts of biological wastewater treatment technologies (BWTTs) can be evaluated by life cycle assessment (LCA). However, very few efforts have been made to expand the ranges of results acceptance and promote stakeholders to participate in the results analysis. To facilitate the evaluation reaching more wide and deep understanding, this study proposed to employ multiple weighting methods and the Conjoint Analysis. To investigate the feasibility, an illustrative case of a bioaugmented constructed wetland was carried out. Weighting results indicated that appropriate improvement strategies could be obtained from synthesizing the similarities and differences of LCA results due to different weighting methods employed. Meanwhile, application of Conjoint Analysis was conducive to the communication between LCA practitioners and BWTTs stakeholders. In a simulated decision-situation, this study found that the decision-making process of stakeholders could be clearly derived to indicate how stakeholders would take trade-offs and make choices based on analyzing LCA outcome.

1. Introduction

Biological wastewater treatment technologies (BWTTs) serve to remove pollutants in bioreactors and waste sites (Barton et al., 1996; Grady et al., 2011). Different types of BWTTs have been developed aiming to remove various pollutants, such as nitrogenous compounds, pesticides, and heavy metals (Belhateche, 1995; van Loosdrecht and Brdjanovic, 2014). However, the implementation of BWTTs is usually

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accompanied by huge consumption of chemicals and energy, thus resulting into enormous emissions towards environment, which could cause adverse environmental impacts (Muga and Mihelcic, 2008). To minimize the environmental burdens, all impacts occurring throughout the whole process of BWTTs should be considered. Life Cycle Assessment (LCA) presents a standardized and sophisticated approach that quantitatively evaluates the environmental impacts of techniques, processes or services throughout their entire value chains (Hellweg and Mila, 2014). Recent progress has demonstrated that LCA can be applied to evaluate the environmental impacts of BWTTs and identify the optimization strategies to improve their process performance and also mitigate their negative environmental impacts (Barton et al., 1996; Cherubini et al., 2009; Edwards et al., 2017; Mu et al., 2016).

Weighting approaches have been used in some LCA studies focusing on the evaluation of BWTTs (Bai et al., 2017; Eriksson et al., 2007; Wang et al., 2015). By assigning relative weights to different environmental categories, single index is generated to represent the environmental impacts of one BWTTs scenario. With the single index, explicit comparison can be achieved among different BWTTs scenarios. This can facilitate the decision-making process because the comparison clearly indicates the environmental impacts of different scenarios. (Bengtsson and Steen, 2000; Finnveden, 1999). It should be noted that most of these studies only employed one weighting approach, which is generally corresponded to one set of ideological profile (Huppes et al., 2012). However, LCA results are usually presented to different groups of stakeholders, which may contain various sets of ideological profiles. Within this context, one weighting approach possibly leads to arbitrary and unreliable results. To enhance the reliability of LCA results, it is thus necessary to adopt multiple weighting methods considering diverse ideological profiles, and to carry out evaluation of LCA results from different perspectives. Regarding the LCA of BWTTs, two distinctive demands were generally involved: (1) to mitigate their regional negative environmental impacts by enhancing the removal of pollutants and (2) to evaluate and tackle their impacts at a global-scale (e.g. including their impacts on resource depletion or global warming). In order to meet the two demands, it was of great importance to adopt, at least, two types of weighting methods for the LCA of BWTTs, i.e. one type for regional context and another one for global context.

Furthermore, to report LCA evaluation of BWTTs, another approach is to directly present impact results without any weighting approach involved (Edwards et al., 2017; Fernandez-Lopez et al., 2015; Mu et al., 2016; Pasqualino et al., 2009; Summers et al., 2015). A key characteristic of the approach is that all information is transferred from LCA practitioners (LPs) to other people such as stakeholders of BWTTs. However, it is worth noting that recently there has been an increasing demand to include the stakeholders of BWTTs into the analysis of LCA results (Guest et al., 2009). It is reasonable to believe that the stakeholders of BWTTs may have more in-depth understandings of real-world performance of BWTTs, which lead them to derive different implications from the LCA results. Although there were some efforts by LPs to deepen and expand the interpretations of LCA outcomes, such as using endpoint impact categories or integrating LCA with other methodologies (Corominas et al., 2013; Jeswani et al., 2010), these efforts did not necessarily involve stakeholders of BWTTs to into the analysis of the LCA results. Thus, it is impending to introduce specific techniques to promote stakeholders of BWTTs to analyze LCA results from different perspectives. This issue can be addressed by employing Conjoint Analysis (CA), which is an efficient approach that has been widely applied for evaluation of environmental products, services and processes (Alriksson and Oberg, 2008). A core function of CA is to allow respondents to derive utilities from environmental scenarios and decompose the utility into part-worths relating to different attributes of those environmental scenarios (Green et al., 2001; Green and Srinivasan, 1978; Rao, 2014). It is thus possible for stakeholders of BWTTs to use CA to determine the best scenario based on LCA outputs and demonstrate the rationale for decision-making.

To address the aforementioned issues, the purpose of this study was to provide methodology basis by expanding the ranges of LCA results acceptance via multiple weighting methods, and by promoting the communication between LCA practitioners and BWTTs stakeholders via CA. This study was conducted (1) to present the importance and benefits of the use of multiple weighting methods for the LCA of BWTTs; (2) to demonstrate the feasibility of applying CA in involving stakeholders of BWTTs in the analysis of LCA results. To comprehensively elaborate the approach, an illustrative case study on the bioaugmentation of a constructed wetland and the evaluation of associated LCA results was carried out. Based on the case, both global-scale and regional-scale weighting methods were employed to investigate how they could contribute to the acceptance of the LCA results in different groups of stakeholders with different ideological profiles, and CA was used to demonstrate how to clarify the criteria based on the LCA outputs and promote stakeholders of BWTTs to use LCA results in their decisions-making process.

2. Methods and materials

2.1. Case description

This work employed a typical BWTT, that is, a bioaugmented constructed wetland (CW). The CW unit was 50 cm length × 40 cm width × 55 cm depth planted with calami and bioaugmented by dosing microbial inocula. The amount of microbial inocula had a concentration of 5.8×10^8 MPN/mL. In addition, the microbial inocula was mixed by three groups of microorganisms, including (1) heterotrophic nitrifying bacterium, (2) autotrophic nitrifying bacteria and (3) a commercially available complex agent BZT®.

The unit was employed to treat raw sewage under operational temperature of 10 °C. The characteristics of the raw sewage were as follows: on average $COD_{influent}$ of 215 mg/L, NH_4^+-N of 42.5 mg/L, TN of 50 mg/L, TP of 2.5 mg/L, and dissolved oxygen of 0.8 mg/L. A control CW unit (non-bioaugmented CW) was also established and operated under the same conditions except the addition of microbial inocula. The production of microbial inocula included three procedures: inocula preparation, inocula cultivation, and subsequent process. The details of each procedure were described in our previous studies (Zhao et al., 2016; Zhao et al., 2017).

2.2. Life cycle assessment with multiple weighting methods

Environmental impacts of the bioaugmented CW were assessed using LCA (Fig. 1). Three scenarios of bioaugmentation were defined: (1) bioaugmented CW, (2) non-bioaugmented CW, and (3) raw wastewater. The functional unit was 100 L of wastewater treated by CW for one cycle. System boundaries covered the operational stage of CW and the inocula production processes. Inventory data was described in the previous study (Zhao et al., 2017). CML was selected as an impact-assessment method, and the impact categories included acidification (A), eutrophication (E), human toxicity (HT), photochemical oxidation (PO), global warming (GW) and abiotic depletion of fossil fuels (ADF). Weighting methods were applied to obtain single index for each scenario. The global-scale weighting methods included BEES (Building for Environmental and Economic Sustainability), EPA (Environmental Protection Agency), and EDIP (Hauschild and Potting, 2005; Huppes et al., 2012). Considering that the bioreactor was operated in China, this study also employed three regional-scale weighting methods that were designed specifically for China context, including YANG factors, LIN factors and ECER (Lin et al., 2005; Wang et al., 2011; Yang and Nielsen, 2001).

2.3. Conjoint Analysis

CA was employed to construct a decision situation for stakeholders