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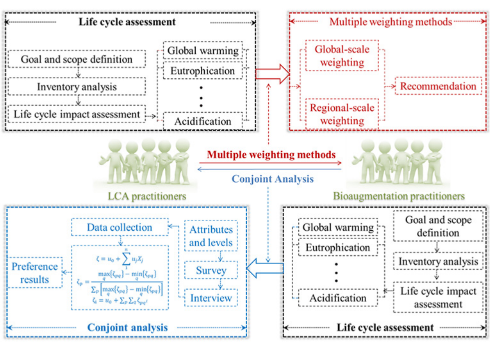
# Engaging multiple weighting approaches and Conjoint Analysis to extend results acceptance of life cycle assessment in biological wastewater treatment technologies

Shunwen Bai[a], Xinyue Zhao[a,c], Dawei Wang[b], Xuedong Zhang[c], Nanqi Ren[a,*]

[a] State Key Laboratory of Urban Water Resource and Environment, School of Environment, Harbin Institute of Technology, Harbin 150090, China
[b] Department of Mechanical and Nuclear Engineering, Virginia Commonwealth University, 800 E Leigh St, VA23225 Richmond, USA
[c] Section of Sanitary Engineering, Department of Water Management, Delft University of Technology, Delft 2628CN, The Netherlands

## 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

* Corresponding author.
*E-mail address:* rnq@hit.edu.cn (N. Ren).

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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 $5.8 \times 10^8$ 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

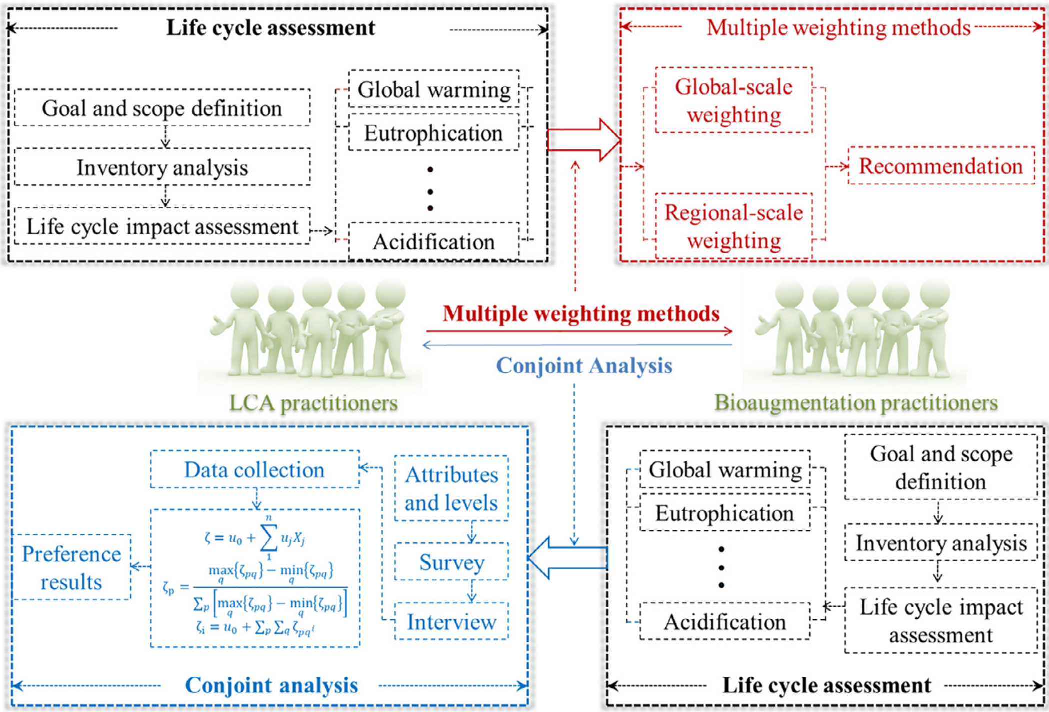


**Fig. 1.** The framework of the evaluation of bioaugmentation in the present work.

of BWTTs to make selections and exhibit preferences based on the LCA results (Fig. 1). Attributes for bioaugmentation were identified by the impact categories of LCA, including ADF, GW, A, E, HT, and PO. Each attribute was assigned to have three levels, implying different states of bioaugmentation. Based on the combinations of attributes and levels, a set of 18 bioaugmentation alternatives was constructed using an orthogonal test design. Respondents will be invited to score the alternatives with values ranging from 1 to 18. The value of 1 represented the most preferred alternative, and the value 18 was the least preferred alternative. The CA model was used to analyze the preference data and obtain estimates results. The types of results included the utility estimates for each level of attributes ($\zeta_{pq}$), the total utility for bioaugmentation scenarios ($\zeta_{\mathrm{i}}$), and the relative importance of each attribute ($\zeta_{\mathrm{p}}$).

The basic CA model was described as (Rao, 2014):

$$Y = X\zeta + \epsilon \tag{1}$$

where Y was the ranking data of bioaugmentation alternatives, X was a set of dummy variables for the combinations of attributes and levels, and $\zeta$ and $\varepsilon$ represented the utility as and the random error of the basic model, respectively. Multiple regression model was engaged to estimate $\zeta$:

$$\zeta = u_0 + \sum_{1}^{n} u_j X_j \tag{2}$$

where $u_0$ was a constant, $n$ was the number of dummy variables, $X_j$ represented the dummy variable that is numbered with $j$, and $u_j$ was the regression parameter of $X_j$. Based on Eq. (2), $\zeta_{pq}$ could be obtained, representing the utility estimates of the $q$-th level of the $p$-th attribute. Furthermore, the relative importance of attributes was calculated as follows (Junior and Joseph, 1992):

$$\zeta_{\mathrm{p}} = \frac{\max_q\{\zeta_{pq}\} - \min_q\{\zeta_{pq}\}}{\sum_p [\max_q\{\zeta_{pq}\} - \min_q\{\zeta_{pq}\}]} \tag{3}$$

where $\zeta_{\mathrm{p}}$ referred to the importance value of the $p$-th attribute, representing the relative importance of the impact category $p$ perceived by the respondents. The overall preferences of the respondents on each bioaugmentation scenario were obtained using the following equation (Churchill and Iacobucci, 2006):

$$\zeta_{\mathrm{i}} = u_0 + \sum_{p} \sum_{q} \zeta_{pq^i} \tag{4}$$

where $\zeta_{\mathrm{i}}$ was the total utility of the $i$-th scenario, representing the overall preference on the $i$-th bioaugmentation scenario. Three scenarios were considered in this study: the bioaugmented CW, the non-bioaugmented CW and the untreated raw wastewater.

In this study, CA was conducted at both an individual level and group level. Firstly, this study invited 3 individuals (S1, S2 and S3), who belonged to the stakeholders of BWTTs, to participate in the LCA results analysis. The ranking data were separately processed, and the results ($\zeta_{pq}$, $\zeta_{\mathrm{i}}$, $\zeta_{\mathrm{p}}$) were analyzed for each individual. Then the ranking data were combined to obtain the results indicating the collective preferences of the three individuals (denoted as T3). In this way, how the differences between individuals' determinations would affect their collective preferences was investigated. Furthermore, this study constructed a decision-group consisting of 30 respondents who were stakeholders of BWTTs or familiar with the bioaugmentation techniques. The 30 respondents were asked to participate in LCA results analysis when they were not informed (namely as NI-30). After the preference data were harvested, the 30 respondents were informed with the case descriptions and bioaugmentation alternatives (namely as I-30), and were invited to demonstrate preference once again. By analyzing the results variance between NI-30 and I-30, this study could identify the influence of extra information on the decisions and preferences of stakeholders of BWTTs.

## 3. Results and discussion

### 3.1. Case results

#### 3.1.1. Multiple weighting methods for LCA evaluation of bioaugmentation

Fig. 2 shows the comparison between bioaugmented CW and non-bioaugmented CW in terms of total environmental impact. Higher values represented higher impacts (Myllyviita et al., 2012; Pfister et al.,

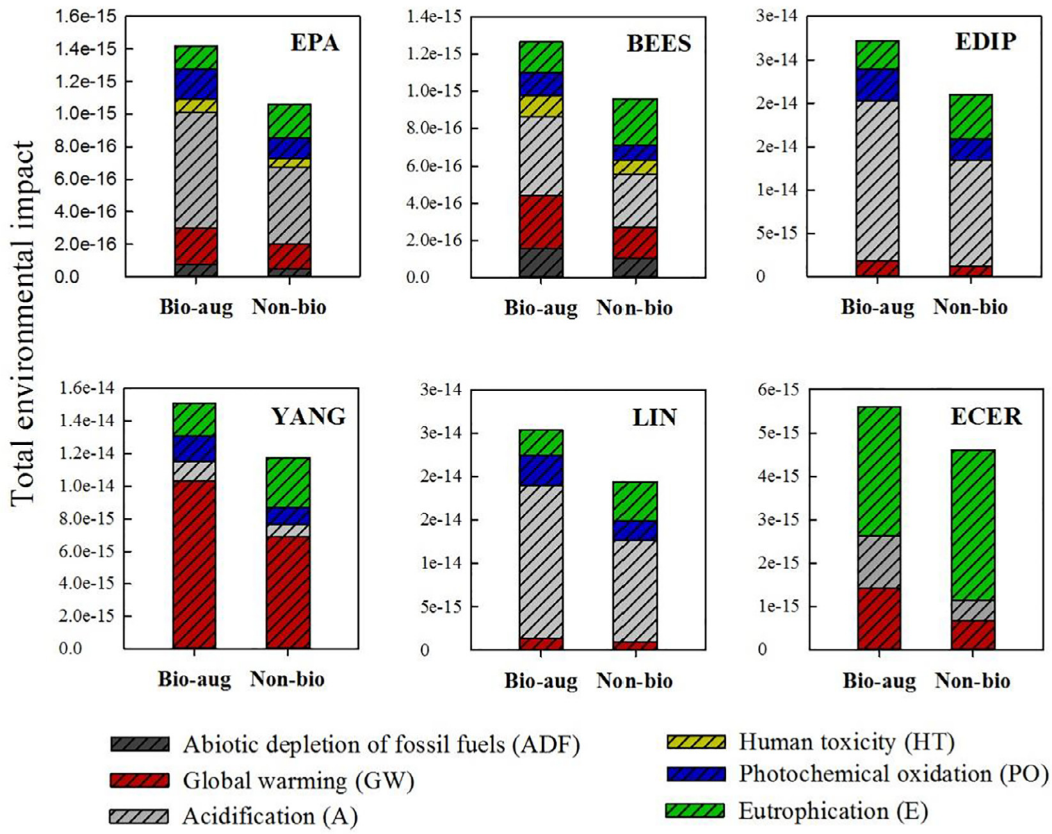


**Fig. 2.** Comparison of total environmental impacts between bioaugmented CW and non-bioaugmented CW using different weighting methods.

2009). As indicated by Fig. 2, bioaugmented CW presented higher values than non-bioaugmented CW, regardless of the weighting methods employed.

Regarding the contributions from impact categories, different weighting methods have demonstrated different contributions (Fig. 2). Acidification (A) could be identified as the major contributors for all the global-scale weighting methods, but different contributions were identified (55.30 ± 0.10% in EPA, 34.80 ± 0.08% in BEES, and 77.10 ± 0.06% in EDIP). For the regional-scale weighting methods, the dominant contributors were substantially different (Fig. 2). Specifically, GW contributed nearly 79.20 ± 0.05% in YANG, A accounted for 78.20 ± 0.05% in LIN, and E represented 60.50 ± 9.87% in ECER.

Factors that were responsible for the environmental impacts were investigated, including the phases of pumping the bioaugmented CW (Pumping phase), operating the bioaugmented CW (Operation), inocula preparation (IP), inocula cultivation (IC), and subsequent process (SP). When using the EPA, EDIP, BEES, YANG and LIN, the pumping phase seemingly was the dominant factor influencing the environmental impact, as shown in Fig. 3 for the contribution analyses of the bioaugmented wetland. When implementing the ECER method, the operation phase presented the highest environmental impacts, followed by the pumping phase.

The environmental impacts of the pumping phase and operation phase were mainly on global warming, acidification, and eutrophication, which are substantially dependent on the emissions of $SO_2$, $CO_2$, COD and $NH_3$. To examine whether the LCA results were sensitive to the changes in the emitted parameters, and to further analyze the uncertainty, sensitivity analysis was carried out for each weighting method. The bioaugmented CW was set as a base case, and the variation of each parameter was assumed to be ± 10% and ± 20%. As shown in Fig. 4, both COD and $NH_3$ presented evident impacts on the results of ECER method, compared with the results of other weighting methods. The result was consistent with the observation that E was identified the major contributor for the environmental impact in ECER (Fig. 2). $CO_2$ showed more substantial impacts in the results obtained using BEES, EPA and ECER. $SO_2$ presented considerable effects in all the weighting methods. The result indicates that, regardless of the employed weighting methods, $CO_2$ and $SO_2$ were the major reduction targets to improve the environmental impacts resulted from bioaugmented CW.

### *3.1.2. Involvement of stakeholders of BWTTs in LCA results analysis using CA*

To facilitate the communications between LPs and stakeholders of BWTTs, CA was employed to promote stakeholders of BWTTs to decide the most preferred bioaugmentation alternative, and quantitatively present their criteria behind the decision (Reap et al., 2008). Utility estimates for each level of an attribute are shown in Table 1. A higher value of utility represented a greater extent of preference (Green et al., 2001). For example, with respect to the S1′s preference for GW, the highest preference was on the raw state (0 kg-$CO_2$-eq.) corresponding with the highest utility of −0.33; and the lowest preference was on the non-bioaugmented state (39,200 kg-$CO_2$-eq.) corresponding with the lowest utility of −1.00. The three individuals (S1, S2 and S3) demonstrated different preferences to ADF, GW, A, and HT, but similar tendencies for E and PO. When all the three individuals' preferences were considered jointly, the collective preferences were presented in the utility estimates of T3. Specifically, for the attribute E, the bioaugmented state presented the highest utility of 9.00. For other attributes, the raw state was the most preferred alternative. Moreover, with respect to the utility comparison between NI-30 and I-30, different preferences were observed for several attributes. In terms of the attribute E, NI-30 showed negligible preference, while I-30 showed strong preferences. In terms of the attribute A, a decreasing preference from the raw state via bioaugmented state to non-bioaugmented state was demonstrated by NI-30, while an increasing tendency was shown by I-30.

Based on the utility estimates of attribute levels, total utility for the

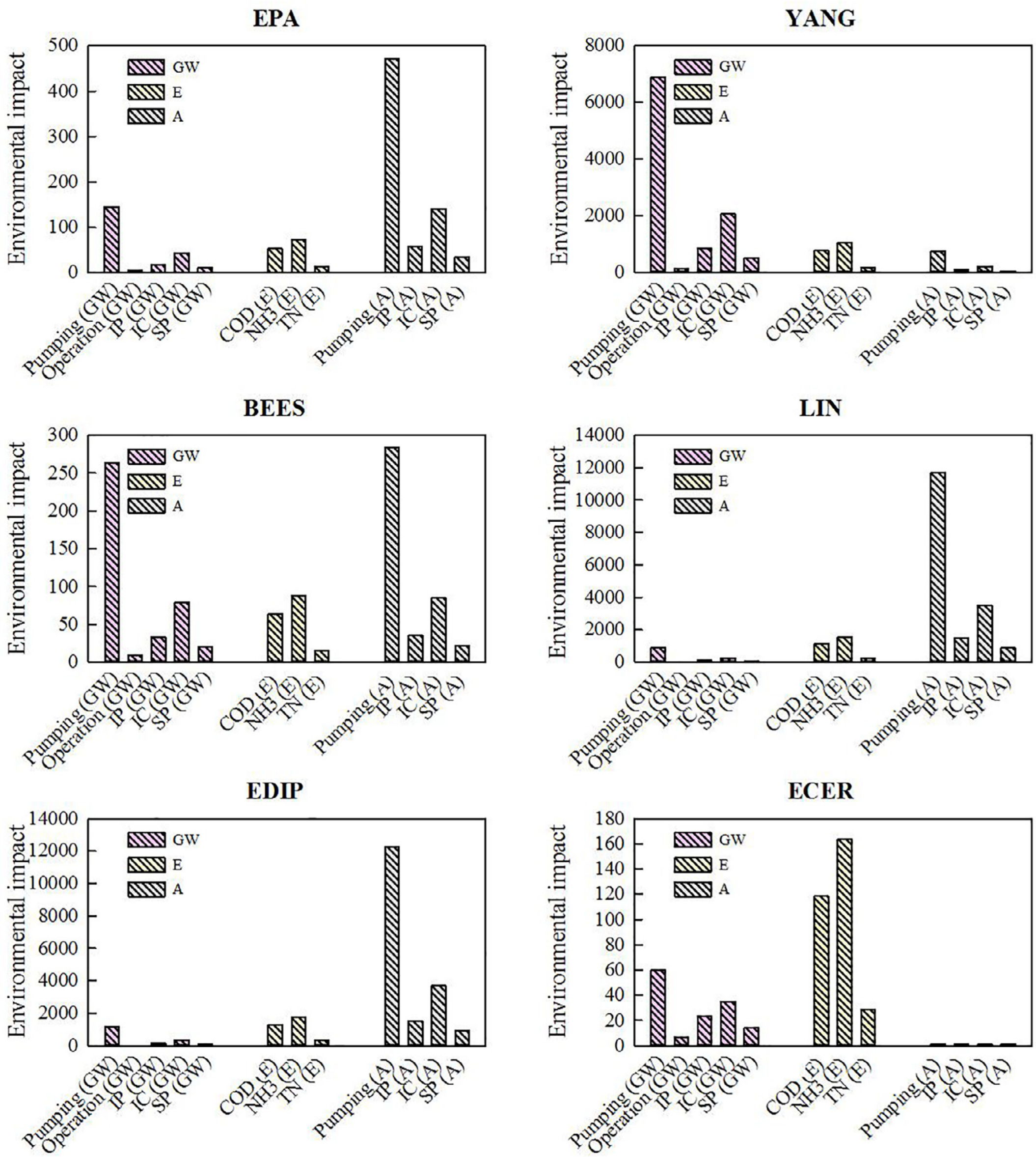


**Fig. 3.** Contribution analyses of the factors influencing the environmental impact of bioaugmented CW.

three case scenarios could be calculated (Fig. 5). The total utility represented the overall preference of respondents to each scenario. With respect to the three individuals (S1, S2 and S3), they demonstrated similar overall preferences, with the bioaugmented CW being the most preferred scenario (6.33 ± 0.33), followed by the non-bioaugmented CW (2.00 ± 0.10) and the raw wastewater (1.67 ± 0.12). Similar rankings of scenarios were shown by T3, reflecting the collective judgement of the three individuals. Moreover, the comparisons of scenarios were different between NI-30 and I-30. The mostly preferable scenario for NI-30 was the raw wastewater scenario (7.75 ± 0.11), but for I-30 the bioaugmented CW (6.33 ± 0.20). The least preferred scenario for NI-30 was the non-bioaugmented CW (2.58 ± 0.13), but for I-30 the raw wastewater scenario (1.67 ± 0.12).

The relative importance of attributes valued by respondents could be measured using a CA method (Fig. 6). The attribute E presented the highest relative importance (66.70%) for the three individuals (S1, S2 and S3), implying the highest environmental priority of E in T3. The two individuals (S1 and S3) showed that ADF was with the relatively second-highest importance (22.20%), whereas no importance value was assigned to GW. In contrast, S2 showed no preference on ADF, but the second-highest preference on GW. As a result, the differences led to a higher importance value of ADF (14.81% in T3) than that of GW (7.41% in T3). Moreover, NI-30 and I-30 also showed some differences. For example, attribute HT presented the highest importance value (65.45%) in NI-30, followed by ADF (21.82%) and GW (5.45%); however, attribute E was with the highest relative importance (66.67%) in I-30, followed by HT (22.22%) and ADF (5.56%).

Based on the aforementioned results, a decision-making process could be derived to describe how respondents took trade-offs facing the three case scenarios. All the three individuals (S1, S2 and S3) belonged to stakeholders of BWTTs, and could reasonably pay more attention to the effects of the enhanced removal of water pollutants in the bioaugmented wetland among the three scenarios. Considering that one critical effect was to reduce eutrophication potential, the alternative that resulted in the lowest eutrophication potential becomes the most preferable option (i.e. bioaugmented CW in this case).

Moreover, this case indicates that additional information to the respondents could significantly influence the results of evaluation of bioaugmentation. When no information about the scenarios of bioaugmentation treating wastewater was present to the 30 respondents, HT was their first consideration regarding the environmental priorities of attributes (Fig. 6), and the scenario that had the

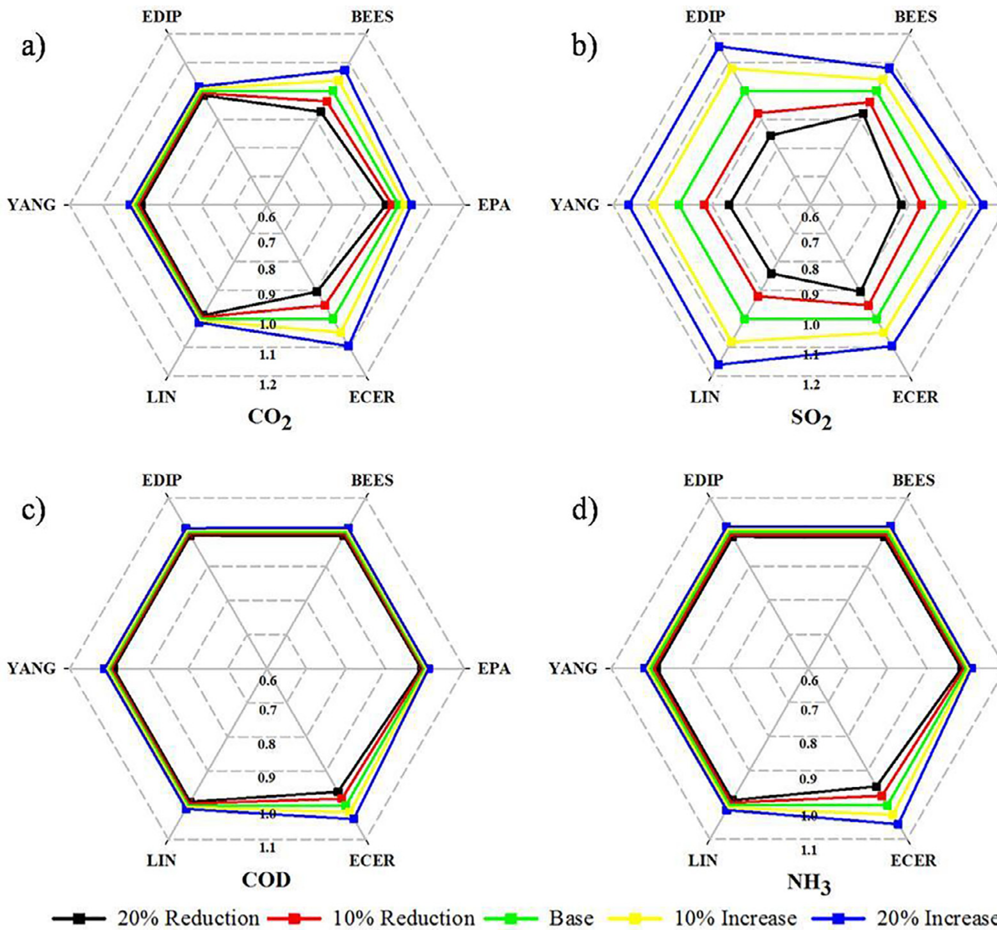


**Fig. 4.** Sensitivity analysis of the parameters influencing the total environmental impact of bioaugmented CW.

**Table 1**
Utility estimates for each level of attributes.

| Attributes | Levels[1] | State | Utility estimates[2] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | T3 | S1 | S2 | S3 | NI-30 | I-30 |
| ADF | 0 | Raw | −0.67 | −1.00 | 0.00 | −1.00 | 3.00 | −0.25 |
| (MJ) | 537,200 | Bioaug | −1.33 | −2.00 | 0.00 | −2.00 | 2.00 | −0.50 |
| | 390,400 | Non-bioaug | −2.00 | −3.00 | 0.00 | −3.00 | 1.00 | −0.75 |
| GW | 0 | Raw | −0.33 | 0.00 | −1.00 | 0.00 | 0.75 | 0.00 |
| (kg-CO2-eq.) | 54,200 | Bioaug | −0.67 | 0.00 | −2.00 | 0.00 | 0.50 | 0.00 |
| | 39,200 | Non-bioaug | −1.00 | 0.00 | −3.00 | 0.00 | 0.25 | 0.00 |
| A | 0 | Raw | −0.14 | −0.25 | −0.25 | 0.08 | 0.50 | 0.08 |
| (kg-SO2-eq.) | 3100 | Bioaug | −0.28 | −0.50 | −0.50 | 0.17 | 0.33 | 0.17 |
| | 2200 | Non-bioaug | −0.42 | −0.75 | −0.75 | 0.25 | 0.17 | 0.25 |
| E | 2169 | Raw | 3.00 | 3.00 | 3.00 | 3.00 | 0.00 | 3.00 |
| (kg-PO4-eq.) | 478.5 | Bioaug | 9.00 | 9.00 | 9.00 | 9.00 | 0.00 | 9.00 |
| | 660 | Non-bioaug | 6.00 | 6.00 | 6.00 | 6.00 | 0.00 | 6.00 |
| HT | 0 | Raw | −0.03 | 0.08 | 0.08 | −0.25 | 3.00 | −1.00 |
| (kg-1,4-dB-eq.) | 1210 | Bioaug | −0.06 | 0.17 | 0.17 | −0.50 | 2.00 | −2.00 |
| | 860 | Non-bioaug | −0.08 | 0.25 | 0.25 | −0.75 | 1.00 | −3.00 |
| PO | 0 | Raw | −0.17 | −0.17 | −0.17 | −0.17 | 0.50 | −0.17 |
| (kg-ethylene-eq.) | 103.7 | Bioaug | −0.33 | −0.33 | −0.33 | −0.33 | 0.33 | −0.33 |
| | 75 | Non-bioaug | −0.50 | −0.50 | −0.50 | −0.50 | 0.17 | −0.50 |

*Note:* [1]For the E attribute, the bioaugmented CW and raw wastewater indicated the lowest and highest level, and the middle level was represented by the non-bioaugmented CW. For all other attributes, the lowest level was observed in the state of raw wastewater, followed by the non-bioaugmented CW (the middle level) and the bioaugmented CW (the highest level).

[2] Utility estimates were obtained for the three individuals (S1, S2 and S3), and their collective preference were measured (T3). Moreover, for the decision-group consisting of 30 stakeholders of BTWWs, utility estimates were calculated when they were not informed (NI-30) and after they were informed (I-30).

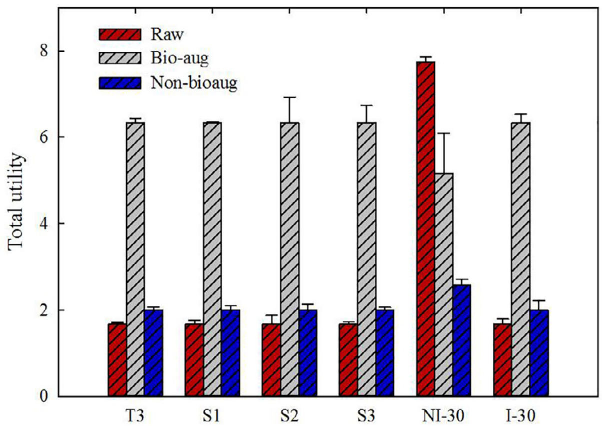


**Fig. 5.** Estimation of total utility for CA.

lowest HT level (raw wastewater) was identified as the most preferred scenario (Fig. 5). After the respondents were informed of the results of the evaluation of bioaugmentation, the E turned to be the major concern, and the bioaugmented CW that presented the lowest E potential became the most preferred scenario.

### 3.2. Implications for the LCA evaluation of BWTTs

This study demonstrated that the joint application of multiple weighting methods and CA could enhance the explanatory ranges of LCA results towards global-scale and regional-scale contexts, and could promote stakeholders of BWTTs to determine the mostly preferred scenario based on their professional judgement. Appropriate strategies to improve BWTTs could be obtained from synthesizing the similarities and differences of LCA results due to different weighting methods employed. Clear decision-making process could be clearly derived via CA to indicate how stakeholders of BWTTs would take trade-offs and make choices based on analyzing LCA outcome.

Based on the evaluation of bioaugmented CW, a few implications were derived for the evaluation of BWTTs using LCA. Using multiple weighting methods was consistent with the general requirements for effective evaluation in the assessment environmental impacts (Bengtsson and Steen, 2000). One of the important requirements was to promote the LCA results to achieve wide acceptance. Specifically, using different weighting methods could make the results accepted by people with different contexts. In terms of the evaluation of BWTTs, regionalized weighting methods were conducive to facilitating the acceptance by stakeholders who focused on the improvement of regional environments. The global-scale weighting methods provided a platform for the bioaugmentation being evaluated from a larger scale.

Besides presenting LCA results to stakeholders, it is necessary to derive improvement strategies from LCA results for stakeholders. However, it is unreasonable to develop strategies from the results based on one specific weighting method, because a method could cause significant bias (Pieragostini et al., 2012; Reap et al., 2008). Although the application of multiple weighting methods was proposed herein, it is still noteworthy that different improvement strategies could be produced due to the results variance obtained from different weighting methods. This issue has been the criticism of stakeholders with diverse backgrounds to LCA results. To address the issue, it is necessary to propose strategies that could consider the similarities and differences in LCA results, and overcome the influences due to weighting methods. Specifically, it is urgently suggested to boost the coordination amongst different methods and construct common recommendations that could help different groups of people reach an agreement on improving the performance of BWTTs in environmental impacts. In the case study, for example, all the results indicated that the total environmental impact of bioaugmented CW needs to be reduced, regardless of the global-scale or regional scale weighting methods employed. Meanwhile, high impacts on global warming and acidification were shown by almost all the weighting methods, implying that the emissions of $CO_2$ and $SO_2$ were the major reduction targets for the improvement of bioaugmented CW in the performance. Considering that these emissions were due to the coal consumption for pumping the bioreactor, improvement strategy could include replacement of coal with natural gas or other clean energy sources. Moreover, it was worth noting that the results from ECER method (regional context) stressed the impact of water pollutants on eutrophication, indicating that efforts were also required for bioaugmented-CW to further enhance the performance in removal of pollutants.

This present study also proposed to employ CA to encourage stakeholders of BWTTs to involve in the analysis of LCA results. A prerequisite for using CA in this study was to convert the impact categories of LCA into the attributes of CA. Generally, one of the most important steps of carrying out CA was to determine which attributes to use (Alriksson and Oberg, 2008; Sarkar et al., 2017). When there were external markets (e.g. commodity market) existing, it was relatively easy to identify the attributes because most of them (e.g. price, brand or performance) could be obtained directly from market surveys. However, few external markets were existed for BWTTs alternatives that belonged to the environmental processes or services, and thereby no attribute could be obtained directly from any market survey. In the present study, in fact, the LCA constructed a hypothetical market in which the environmental impact of BWTTs alternatives were categorized into a list of impact categories. By assigning the impact categories as attributes, it ensured a smooth application of CA to promote

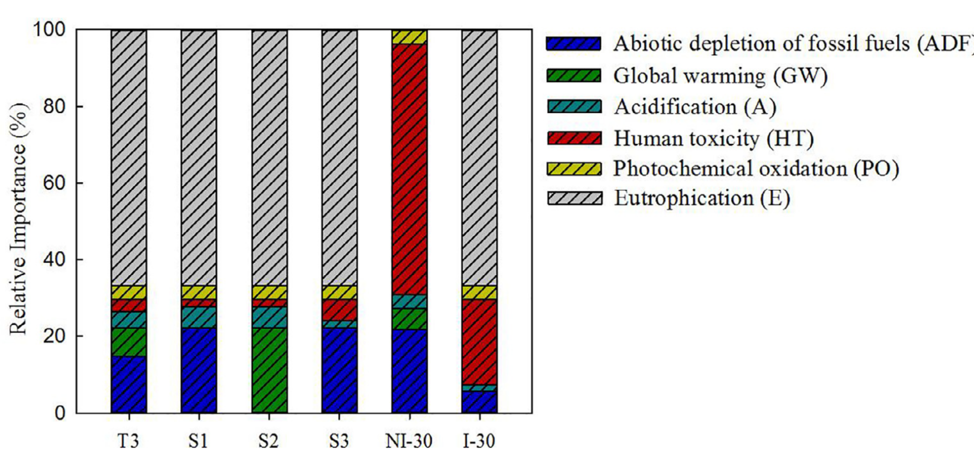


**Fig. 6.** Estimation of relative importance of different attributes.

stakeholders of BWTTs in to be involved in evaluation of LCA results on bioaugmented processes.

Another important factor to take into account was the sample size for conducting CA (Orme, 1998). In general, it was highly related to the purpose of CA when considering whether the sample was statistically representative. In this study, one of the purposes was to investigate the differences between individuals' overall preferences and criteria. Thus, it was reasonable to carry out CA for each individual, and analyzed the differences in the total utilities. Another purpose was to investigate the effect of extra information on the stakeholders of BWTTs' selections on different BWTTs alternatives. To achieve this purpose, a decision group was established for this study consisting 30 individuals in total. This current study interviewed all the 30 individuals, meaning that a comprehensive survey was performed. This indicated that the sample size was equal to the overall size, and no sampling error existed. In future, if more stakeholders are required to perform the survey and a comprehensive survey is difficult to be carried out, it would be necessary to investigate the influence of a sample size on CA results.

## 4. Conclusions

To facilitate LCA evaluation of biological wastewater treatment technologies (BWTTs) to be understood widely and deeply, this study identified two pathways: (1) implementation of multiple weighting approaches and (2) implementation of CA. By means of a case study on a bioaugmented CW, this study concluded that engaging multiple weighting approaches could expand the explanatory ranges of LCA results of BWTTs under both global-scale and regional-scale contexts. Application of CA could promote stakeholders to determine the mostly preferred scenario depending on their own values, knowledge and judgement, which was conducive to the communication between LCA practitioners and BWTTs stakeholders.

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