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Establishing a decision-support system for eco-design of biological wastewater treatment: A case study of bioaugmented constructed wetland

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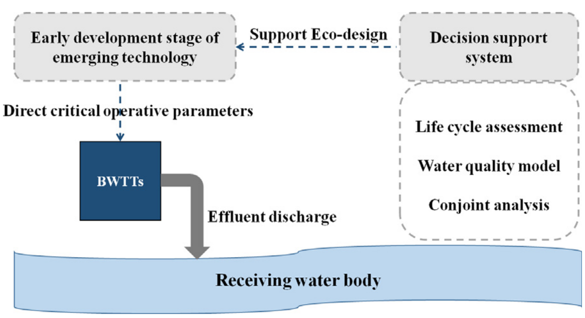
GRAPHICAL ABSTRACT



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ABSTRACT

Deep treatment is a common approach to enhance pollutant removal for biological wastewater treatment technologies (BWTTs), and life cycle assessment (LCA) holds substantial advantages to support process optimization. However, there lacks of LCA-based benchmarks that cover human-nature nexuses and stakeholder involvement, which limits the guidance and eco-design of BWTTs. This study proposed a decision-support system (DSS) by linking LCA with Water Quality Model and Conjoint Analysis. Three major findings were identified based on a demonstrative case (constructed wetland bioaugmented by dosing different microbial inocula): (1) Increasing bacterial intensities would achieve net environmental improvement, but it might not apply to all cases; (2) Making full use of natural self-purification capacity could partly replace the functions of BWTTs; (3) Stakeholders would concern aquatic environmental improvement when receiving river that had limited environmental capacity. Overall, the DSS provided a data-driven platform for screening options before determinations were made to constrain wastewater treatment sustainability.

1. Introduction

Towards the global sanitation target agreed by United Nations, local governments and international organizations, tightening the discharge limits for biological wastewater treatment technologies (BWTTs) have been identified as the primary approach to regulate urban wastewater. This has promoted the intensive development of emerging technologies associated with a wealth of investigations aiming to remove more

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pollutants from BWTTs (Zhou et al., 2018). It is the case for instance of constructed wetlands, bioelectrochemical systems, membrane bioreactors, anammox systems, and etc (Gu et al., 2018; Gupta et al., 2014; Kelly and He, 2014; Zhao et al., 2016). Among those studies, one of the most important topics is to identify critical operative parameters and conditions, and to provide an important benchmark for engineers or researchers to properly direct the operations of BWTTs.

However, controversies surrounding the increased treatment intensity can be generated from the following aspects (Wang et al., 2015). Firstly, increased treatment intensity is usually accompanied by substantial consumptions of materials and energy, inevitably resulting in enormous environmental emissions as well as unintended environmental burdens (Sweetapple et al., 2014). Secondly, current pollutant-removal pressures are mainly concentrated in the BWTTs, but fail to take full advantages of human-nature nexuses (e.g., the natural purification capacity of receiving water and the officially stipulated river functions), which can relatively exacerbate the waste of resources (Liu et al., 2015). Thirdly, sustained strategies for BWTTs operation need to be set by inclusion of stakeholders who have more in-depth knowledge of BWTTs to determine the rationale for decision-making (Bai et al., 2017); otherwise, a one-size-fits-all strategy will lead to limited acceptance due to the arbitrary decision manner with no consideration of inner conflicts and reality.

The aforementioned three elements need to be jointly considered even if the efforts to detect optimal parameters or conditions for enhanced treatment are at an early stage of BWTTs. Without the combined considerations to uncover where potential trade-offs could be made, determining improvement measures will be difficult once the improvement potentials are locked (Hetherington et al., 2014). In this regard, it would be legislative and necessary to evaluate and screen the potential options from a comprehensive perspective on the basis of eco-design. An eco-design refers to the concept of designing products, services or processes with special consideration of environmental impacts during their whole value chains (Knight and Jenkins, 2009). In order to support eco-design of BWTTs, recent studies advocated the application of life cycle assessment (LCA) to select, design and optimize the treatment alternatives, and to generate environmental load data to advance the knowledge needed for forecasting the potential trade-offs as the predetermined parameters and conditions were applied in reality (Arias et al., 2018; Liu et al., 2018). LCA holds the advantages of converting all the energy and material consumptions associated with environmental emissions into the quantitative results within multiple environmental indicators (Zhao et al., 2017; Rahman et al., 2018).

However, significant limitations of LCA appear as the unavailability and difficulty of capturing the dynamic interactions between effluents and receiving water, as well as integrating the officially stipulated objectives into the estimation process (Corominas et al., 2013). Furthermore, another non-negligible issue is that the generated information from LCA could only be transferred from LCA practitioners to other stakeholders. There is a lack of rational scheme to obtain feedback from stakeholders who probably have different understandings and explanations of LCA results based on their professional knowledge about the wastewater management and pollution-treatment process (Bai et al., 2018d). Thus, relying on LCA without fully addressing the two limitations will result in insufficient information and provide a limited benchmark for directing improvement. Thus, there is a critical requirement to expand an in-depth LCA framework for a more comprehensive estimation regarding eco-designs of BWTTs.

To address the aforementioned limitations, the purpose of this study was to introduce a decision-support system (DSS) for linking the environmental impact assessment of BWTTs alternatives with the receiving water's self-purification capacity and officially stipulated river functions (OSRF), and for promoting the involvement of stakeholders' participation. The LCA-based DSS represents the first work to support the eco-design of BWTTs for sustained options of enhanced wastewater treatment. Implementation of the DSS will contribute to avoiding the unsustainable operative parameters identified by the single criterion of pollutant-removal performance. The study covered two aspects: (1) illustrated the methodology basis of the DSS; (2) conducted a case study of a demonstrative constructed wetland (CW) coupled with different bioaugmentation alternatives. This study was applied to demonstrate how the established DSS can facilitate a sustained evaluation and regulation of BWTTs regarding different enhanced treatment alternatives based on the case study.

2. Methods and materials

2.1. Methodology integration of three modeling systems

The DSS was built upon three methodologies: LCA, water quality model (WQM) and conjoint analysis (CA). Specifically, LCA delivered a comprehensive list of environmental indicators by covering a wide area of large-scale environmental aspects, and provided accessible interfaces to plenty of databases (Guinée, 2001; Renou et al., 2008). WQM consisted of a collection of formulations characterizing the fate of pollutants in a water body (transportation and transformation) (Bowie et al., 1985). A methodology integration between LCA and WQW enabled a possibility to generate dynamic impact-assessment results representing the site-specific effects of water pollutants (Bai et al., 2018a,b). CA was an economic model designed to derive stakeholders' preferences by constructing hypothesized bundles of decision scenarios (Rao, 2014). Combined LCA and CA had shown the potential to comprehensively derive and understand how stakeholders from different contexts and with diverse values made selections on the basis of LCA estimation (Bai et al., 2018c,d).

2.2. Case description upon bioaugmented constructed wetland

This work employed a typical BWTT, which was a pilot-scale constructed wetland (CW) coupled with different bioaugmentation alternatives to enhance the removal performance of pollutants. The CWs were with the design of subsurface flow using polyvinylchloride organic glass (50 cm length × 40 cm width × 55 cm depth). The soil was filled in CWs with 15 cm deep, which was collected from topsoil of a CW area. The calami of similar size (approximately 0.85 m in height) were transplanted with biomass of 1.2 kg fresh weight per/m^2. The CWs were set up and operated under conditions at a temperature of around 8–12 °C. Besides, the enriched microbial inocula used in this study was prepared according to previous studies (Zhao et al., 2016, 2017). Three inocula doses (0.1×10^8 MPN/mL, 0.5×10^8 MPN/mL and 1.0×10^8 MPN/mL) were determined as three bioaugmented alternatives, defined as Inocula-0.1, Inocula-0.5 and Inocula-1.0, representing the increased treatment intensities. The effluents of CW were released into the receiving river named the *Ashihe River* that was located in Northern China. Potentially, there were five officially stipulated river functions (OSRF) ranging from Grade-I to Grade-V, each of which corresponded to a specific maximum allowable pollutant concentration (MAPC). Moreover, different downstream distances (DD) were assumed to be affected and examined ranging from 200 m to 70,200 m.

The functional unit for each alternative was the 100 L of the treated wastewater. System boundary covered the operational stage (energy consumption, effluent discharge and air emissions) of CW, the microbial inocula production (inocula preparation, inocula cultivation and subsequent process), and the receiving water (natural factors and artificial factors). Environmental impacts of the three alternatives were firstly evaluated in the DSS by converting the inventory data, river characteristics and OSRF information into the total environmental impacts (TEI) and regional environmental impacts (REI). Secondly, the system was investigated the changing trends of TEI and REI over the different DD and OSRF, and was explored the net environmental improvement (TEI) of paradigm shifts. Furthermore, a group of

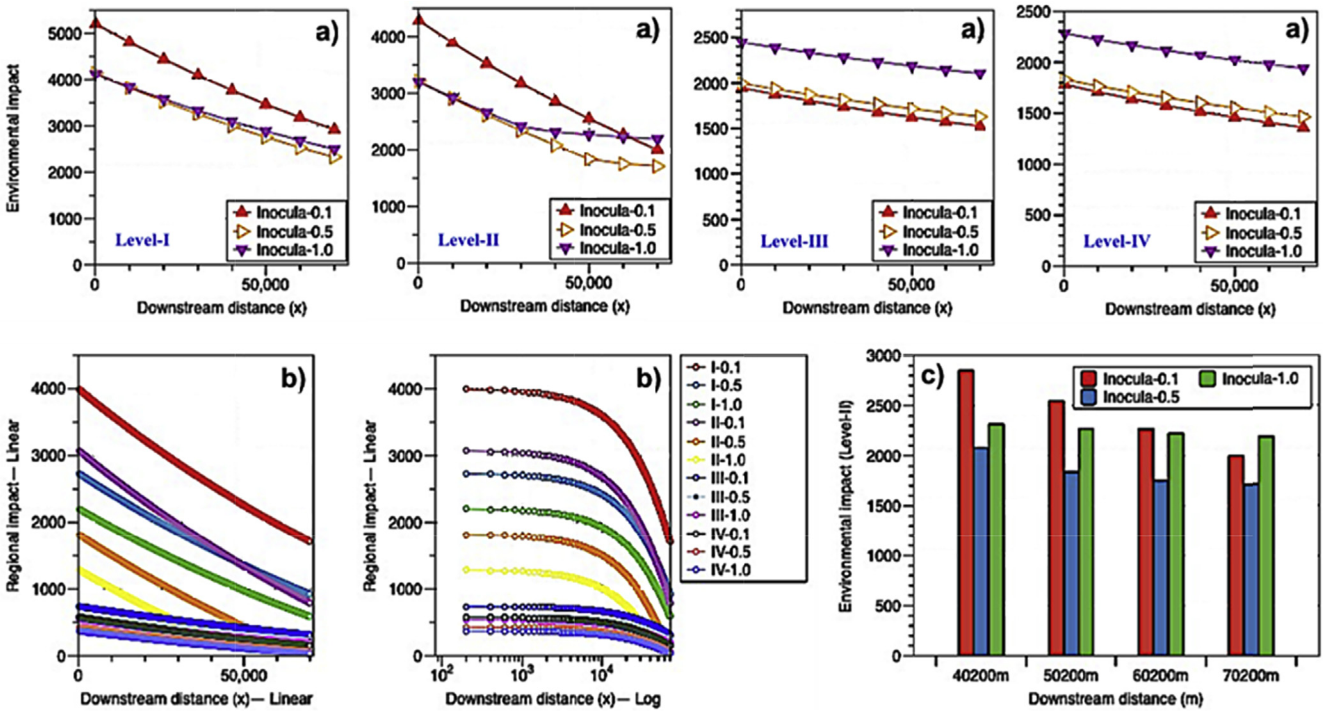

Fig. 1. Environmental impacts of different microbial inocula alternatives upon downstream distances (x) and river functions (Levels); Figure-a) represented for the total environmental impact, Figure-b) represented for the regional impact, and Figure-c) indicated a comparison between alternatives.

stakeholders that were familiar with the wastewater treatment or bioaugmentation was invited to make selections concerning the best option among the three alternatives, and the collective determinations were formed in the DSS via the conduction of CA.

3. Results and discussion

3.1. Environmental impacts of bioaugmentation alternatives

For the three alternatives, dynamic estimations and comparisons of TEI are generated (Fig. 1). For example, regarding the environmental impacts of the Inocula-0.1 alternative at OSRF of Level-1 (Fig. 1-a), different evaluation results were produced at different DD, ranging from 5200 (at DD of 200 m) to 3000 (at DD of 70200 m). Of note, producing dynamic output was one of the most innovative functions of the established DSS, overcoming a principal limitation of LCA that only enabled the static output. In the fluctuated conditions of receiving river and official management, this advantage would facilitate a highly flexible analysis regarding the evaluation, selection and determination of wastewater scenarios.

As shown in Fig. 1-a, the varied TEI occurred when either DD or OSRF changed. Given the static LCA output of global-scale categories, the dynamic values of REI in Fig. 1-b constituted the driving forces for the TEI's formation and fluctuation. With the increase of DD or OSRF, the REI showed declining tendencies. The rationale for this closely corresponded with the incorporation of WQM. Firstly, the self-purification process was involved such that the increased DD would require a longer time for more water pollutants to be self-purified before reaching the monitored section. Secondly, the increasing levels of OSRF specified the increased concentrations of water pollutants which were allowed to be emitted, and hence relatively reduced the number of pollutants.

3.2. Identification of the most proper alternative

Many WWTPs in China were put into a situation to consider whether and how to upgrade, which required an essential decision support for choosing proper treatment alternative. In the case of traditional effluent-quality-based perspective, the Inocula-1.0 alternative was desired due to the maximum pollutant removal efficiency (e.g., 76% for COD and 75% for TN).

However, differences arise when included the environmental impact as an essential criterion. Owing to the lowest TEI at OSRF of Level-I and Level-II, the Inocula-0.5 alternative was the most proper option at all downstream distances (Fig. 1-a). In contrast, both Level-III and Level-IV revealed that the Inocula-0.1 alternative became the option owing to the lowest TEI. Moreover, even if in same OSRF (Level-II), comparisons between alternatives also showed inconsistency at different downstream distances. For instance, the Inocula-0.1 showed the highest TEI (2549.55) at DD of 50200 m, while the Inocula-1.0 became the most dominant one (2187.82) when DD moved to 70,200 m (Fig. 1-c).

3.3. Net environmental improvement of a paradigm shift

An analysis of NEI will produce a more straightforward indication showing whether the potential paradigm shift would achieve improvement in terms of TEI.

As shown in Fig. 2, shifting from Inocula-0.1 to Inocula-0.5 can achieve positive improvement at Level-I and Level-II (NEI < 0 at all downstream distances), but can incur more negative burdens at Level-III and Level-IV (NEI > 0 at all downstream distances). A further shift from Inocula-0.5 to Inocula-1.0 demonstrates more complicated NEI transitions at different OSRF levels. No positive improvement could be achieved for this paradigm shift at Level-III and Level-IV, since the values of NEI were higher than 0 at both OSRF levels, averagely ranging from 450 to 478. However, at Level-I and Level-II, the NEI changed from negative values to positive values. Specifically, as for the OSRF of Level-II, negative values (positive improvement) of NEI were observed from 200 m to 6200 m, whereas, positive values (negative impacts) of NEI were generated from 8200 m to 20,200 m, with the turning points occurring in the DD ranges between 6200 m (-0.1 of NEI) and 8200 m (6.62 of NEI)

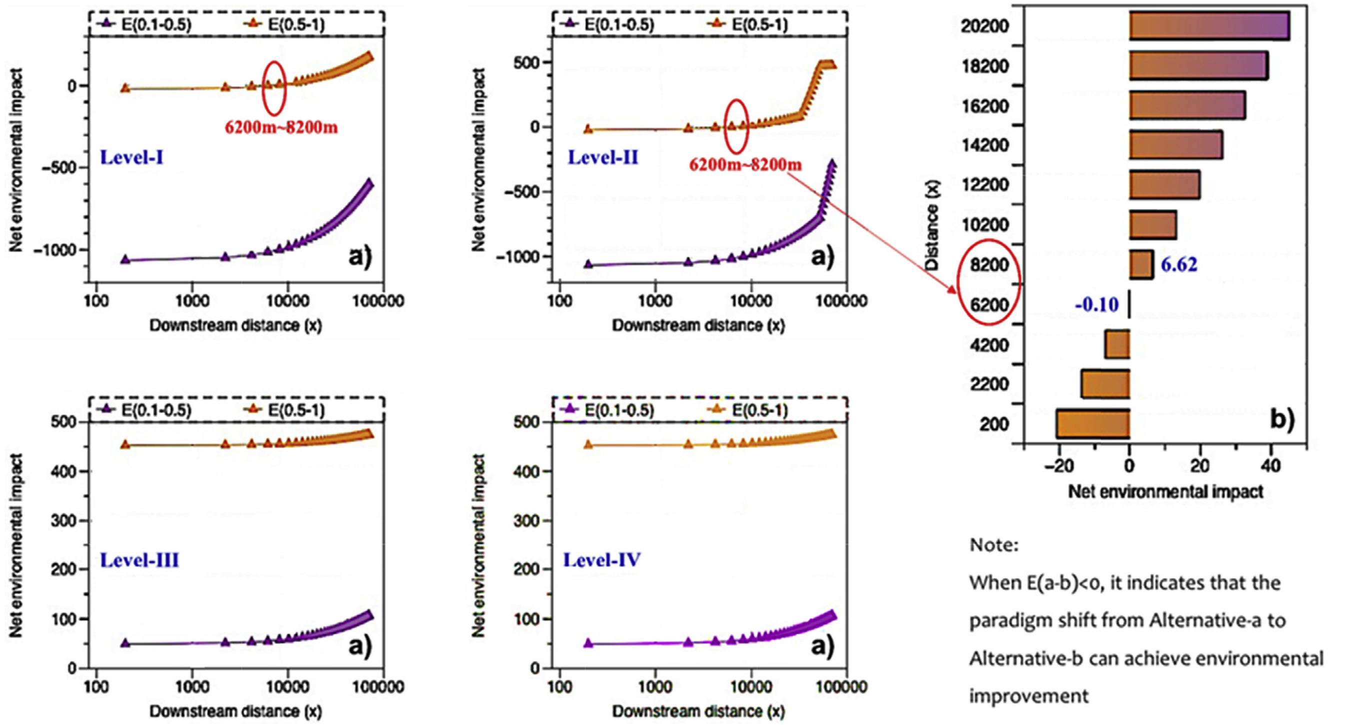

Fig. 2. Net environmental improvement of paradigm shift upon different downstream distances (x) and different river functions (Levels).

3.4. Stakeholder involvement in varied decision scenarios

The involvement of stakeholder's participation was engaged in DSS by using CA. The bioaugmented case examined how different decision scenarios would impact the decision options and the intrinsic criterion of the stakeholders from the context of sewage treatment (Fig. 3).

Firstly, stakeholders demonstrated similar overall preferences in the decision scenario constructed by different DD. As shown in Fig. 3-a, at both DD of 20,000 m and 70,000 m (Level-2), Inocula-0.5 was the most preferred alternative, with the highest total utility of 6.1 and 6.3, respectively. Further, different overall preferences were exhibited in the decision scenario containing different OSRF. During the shift from Level-II to Level-III, the most preferred alternative altered from Inocula-0.5 to Inocula-0.1 (Fig. 3-a). This tendency was consistent with the TEI comparisons shown in Fig. 1-a that the alternative having the lowest TEI was Inocula-0.5 at Level-II whereas Inocula-0.1 at Level-III.

The alternation of stakeholders' overall preferences was a result of the changes of decision criterion when facing different decision sets. The fundamental changes occurred for the relative importance of the attributes for Ac, GW and ADF increased from Level-II (20.0%, 12.7%, and 13.1%) to Level-III (22.0%, 28.6%, 27.2%) (Fig. 3-b). This indicated that stakeholders would assign more environmental priority to the unintended environmental implications when increasing the treatment intensity in the case of the receiving water that was allowed to receive more water pollutants.

3.5. Implications from the bioaugmented case analysis

The DSS system delivered a platform that could estimate the wastewater treatment options before they were implemented to constrain the operation of BWTTs. In addition to the single dimension on pollutant-removal performance, the multiple environmental dimensions (e.g. climate change or resource consumption), human-nature nexuses (e.g. self-purification capacity of receiving water) and stakeholder involvement were introduced by the DSS system, which contributed to the eco-design of BWTTs via facilitating a comprehensive evaluation of the potential impacts in either laboratory scale or pilot scale.

Based on the bioaugmented case study, the main implications were identified as:

(1) Comparisons between different treatment options in terms of TEI vary considerably, depending on which DD or OSRF were

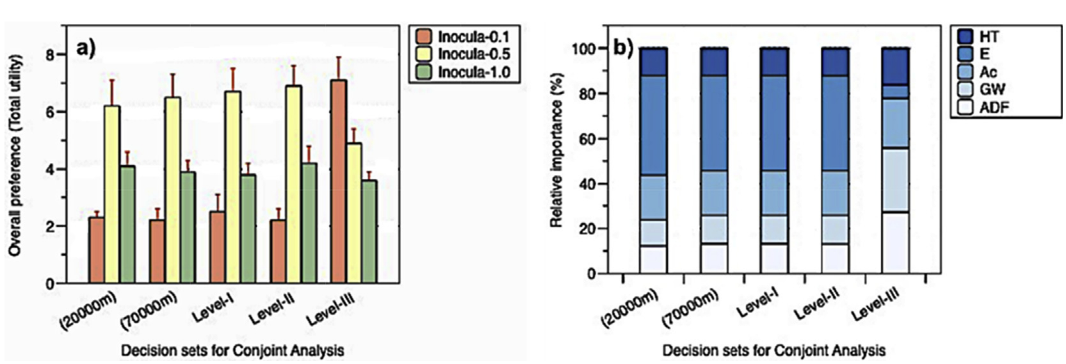

Fig. 3. a) Overall preferences and b) inner criterion of stakeholders under different decision scenarios set by different downstream distances and different river functions.

determined for evaluation. An overall tendency revealed that the TEI relatively decreased with the longer distances of DD (more pollutants degraded owing to self-purification of receiving water) and with the lower levels of OSRF (more pollutants allowed to be released into receiving water).

(2) This study demonstrated that enhancing the treatment intensity of BWTTs could achieve environmental improvement but not for all cases. This was validated quantitatively via the DSS scheme by characterizing the impact of the increased microbial inocula addition under the regulation context of China. With respect to the paradigm shift from Inocula-0.5 to Inocula-1.0, the environmental improvement was found only within the DD of 6200 m at the ORSF of Level-I and Level-II (Fig. 2).

(3) With the change of decision scenarios, stakeholders would shift their evaluation emphasis by adjusting the weights between different attributes. A manifestation of this point was the preference shift demonstrated by the stakeholders in this study, who assigned more weights to the attribute that represented the environmental benefits of enhancing the microbial inocula addition (in the scenario that stipulates Level-I or Level-II to receiving water), while concerned more about the attributes that characterized the unintended environmental burdens (in the case of OSRF level at Level-III).

4. Conclusions

In this study, an integrated DSS was introduced for sustained evaluation of BWTTs based on the combination of LCA, WQM, and CA. The DSS provided a platform that could contribute to pre-estimating and screening of proper treatment options to constrain the operation of WWTPs. The generation of dynamic evaluation outcome was the main advantage of DSS, which could help decision-makers and stakeholders to investigate the sustainability of BWTTs from multiple perspectives rather than a single "pollutant-removal" angle. Future studies are required to refine the modeling system and implement the DSS upon more emerging techniques.

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Appendix A. Supplementary data

Specific comments include the detailed descriptions of materials, formulas, parameters, fundamental input and processing procedures of the DSS, as well as a comprehensive uncertainty analysis regarding the robustness of the modeling outcome. Supplementary data to this article can be found online at https://doi.org/10.1016/j.biortech.2018.12.016.

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