Bioresource Technology 244 (2017) 407–415

Contents lists available at ScienceDirect

Bioresource Technology

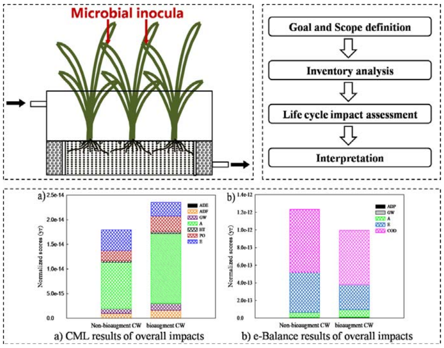
journal homepage: www.elsevier.com/locate/biortech

Evaluation of bioaugmentation using multiple life cycle assessment approaches: A case study of constructed wetland

Xinyue Zhao[a,b], Jixian Yang[a], Xuedong Zhang[b], Li Wang[a], Fang Ma[a,*]

[a] *State Key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology, Harbin 150090, China*
[b] *Section of Sanitary Engineering, Department of Water Management, Delft University of Technology, Delft 2628CN, The Netherlands*

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Bioaugmentation
Life cycle assessment
Environmental impacts
Constructed wetland

ABSTRACT

Bioaugmentation is a promising technology to enhance the removal of specific pollutants; however, environmental impacts of implementing bioaugmentation have not been considered in most studies. Appropriate methodology is required for the evaluation from both in-depth and comprehensive perspectives, which leads to this study initiating the application of life cycle assessment (LCA) of bioaugmentation. Two LCA methods (CML and e-Balance) were applied to a bioaugmentation case with the aim of illustrating how to evaluate the environmental impacts of bioaugmentation from different perspectives based on the selection of different LCA methods. The results of the case study demonstrated that the LCA methods with different methodology emphasis produced different outcomes, which could lead to differentiated optimization strategies depending on the associated perspectives. Furthermore, three important aspects are discussed, including coverage of impact categories, the selection of characterization modeling for specific pollutants, and the requirement of including economic indicators for future investigation.

1. Introduction

Bioaugmentation focuses on improving the bio-removal capacity of organic matter or pollutants by inoculating specific strains or microbial inocula (Dejonghe et al., 2001; Silva et al., 2004). Many studies have shown the feasibility of using bioaugmentation to enhance the treatment of wastewaters containing heavy metals and various organic pollutants, such as nitrogenous compounds and pesticides (Albers et al., 2015; Arjoon et al., 2013; Chen et al., 2015; Karas et al., 2016). For example, a recent study enriched specific microbial inocula and applied

---

* Corresponding author at: State Key Laboratory of Urban Water Resource and Environment, School of Municipal and Environmental Engineering, Harbin Institute of Technology, Harbin 150090, China.
E-mail addresses: X.Zhao-3@tudelft.nl (X. Zhao), mafang@hit.edu.cn (F. Ma).

http://dx.doi.org/10.1016/j.biortech.2017.07.170
Received 15 June 2017; Received in revised form 26 July 2017; Accepted 27 July 2017

the inocula to a pilot-scale constructed wetland (CW) that was operated around 10 °C (Zhao et al., 2016). An enhanced capacity of removal of pollutants was achieved, accompanied with the higher removal efficiency of ammonia nitrogen and total nitrogen by approximate 10% compared with the non-bioaugmented wetland. The results indicated that bioaugmentation was a promising technology to enhance the bioremoval capacity of CW operated at cold conditions.

Most of the studies concerning bioaugmentation concentrated on enhancing the pollutants removal (Fotidis et al., 2014; Pei et al., 2010). However, little literature investigated the potential environmental impact of bioaugmentation. The implementation of bioaugmentation is involved with complex system and elements, generating environmental consequences in different aspects. Generally, the environmental impact of bioaugmentation falls into two categories. On the one hand, bioaugmentation promotes the improvement of regional issues because the enhanced removal of pollutants protects the local receiving water; On the other hand, bioaugmentation has the tendencies of shifting regional issues towards other environmental aspects with global scale such as greenhouse effect, resource depletion or acidification. It is due to the fact that bioaugmentation system involves complicated processes including operation, manufacture, storage and transport, all of which are associated with resource consumption, chemical substance utilization and greenhouse gas emissions.

To facilitate the identification of optimization efforts and support the decision-making, one of the critical steps is to fully explore the environmental impact along the whole process of bioaugmentation. This requires the application of appropriate methodologies that can deal with the environmental impact of bioaugmentation from two perspectives (at least): (1) the in-depth perspective into the effects of enhanced pollutants removal and (2) the comprehensive perspective into other effects such as greenhouse effect, resource depletion or acidification.

Life cycle assessment (LCA) is a useful method to evaluate the potential environmental consequences of different environmental aspects associated with the all stages of techniques, products or services (Corominas et al., 2013; Finnveden et al., 2009; Guinee et al., 2011; Hellweg and Mila i Canals, 2014; Wang et al., 2012). Different types of LCA methods have been developed (Bare, 2011; Guinee, 2001; Jolliet et al., 2003; Nitschelm et al., 2016; Owsianiak et al., 2014). Notably, the selection of LCA method is relevant to the selection of specific perspective investigating the cases or scenarios (Bai et al., 2017b). For instance, selecting site-specific methods was beneficial to the evaluation from the perspective engaging regional characteristics, while choosing site-generic methods was conducive to the evaluation regarding full ranges of negative impacts (Zhou et al., 2011).

This study focused on the investigation of environmental impact assessment throughout a life cycle of bioaugmentation. Two LCA methods (CML and e-Balance) were applied to a bioaugmentation case to illustrate how the selection of different LCA methods could contribute to the environmental assessment from different perspectives. The bioaugmentation case was based on a pilot-scale CW that was operated at 10 °C in China. CML is selected because it is capable of assessing the impacts of wastewater-related initiatives on a broader range due to the established comprehensive coverage of environmental indicators, and e-Balance is chosen because it is designed specifically for China context and it could incorporate several special indicators to address the impacts of wastewater-related initiatives from a deeper perspective.

2. Methods and materials

2.1. Constructed wetlands units

The CW unit, which was with the design of subsurface flow and planted with calami, was 50 cm length × 40 cm width × 55 cm depth (Fig. 1). From bottom to top the unit was filled with gravel with the height of 150 mm and particle size of 3–4 cm, then gravel with the height of 100 mm and particle size of 0.5–1 cm, and soil with the height of 100 mm. The inlet and outlet were located at 50 cm and 5 cm above the bottom, respectively. Two baffles or baffle plates were placed at a distance of 5 cm in front of the inflow and outflow of the gravel bed to intercept big particles and ensure an even distribution of influent.

In this study, two identical CW units were employed for the treatment of raw sewage, which comprised averaged $COD_{influent}$, NH_4^+-N, TN, TP of 215 mg/L, 42.5 mg/L, 50 mg/L and 2.5 mg/L, respectively. Unit (a) was the control group without adding microbial inocula, while the other unit (b) was dosed with the microbial inocula. An average operational temperature for each unit was 10 °C, which was representative temperature for sewage during winter intemperate zones.

2.2. Microbial inocula

Microbial inocula were dosed to unit (b) to enhance nitrogen removal efficiencies under low temperature. Microbial inocula production consisted of three procedures: inocula preparation, inocula cultivation and subsequent process. Autoclaving the microbial medium was the main step in inocula preparation, while inocula cultivation was mainly referred to culturing microbial enrichment in a 10 °C incubator shaker. The microbial inocula consisted of three groups of microorganisms, i.e., (1) heterotrophic nitrifying bacterium, (2) autotrophic nitrifying bacteria and (3) a commercially available complex agent BZT®. The three individuals at the ratio of 1:1:1 were mixed to obtain the inocula with a final cell concentration of approximately 5.8×10^8 MPN/ml. The medium of total inorganic salts contained (per liter): 5.0 g trisodium citrate; 1.0 g NH_4Cl; 0.23 g $MgSO_4{\cdot}7H_2O$; 1.0 g KH_2PO_4; 1.0 g K_2HPO_4; 1.25 g NaCl; 0.2 g $(NH_4)_2SO_4$; 0.25 g NaH_2PO_4; 0.01 g $MnSO_4{\cdot}4H_2O$; 0.5 g $CaCO_3$. After the microbial suspension was obtained, a further centrifugation was needed as the subsequent process to produce the microbial inocula. Then, bioaugmentation of the CW was performed by adding the microbial inocula every 16 days (one cycle).

2.3. Life cycle assessment

2.3.1. Goal and scope definition

The objective of this LCA analysis was to evaluate and compare environmental impacts generated by employing bioaugmented CWs to treat wastewater. With the aim, the following scenarios were formulated:

1) Constructed wetland without addition of inocula (Non-bioaugmented CW).
2) Constructed wetland with addition of inocula (bioaugmented CW).
3) Raw wastewater discharged directly into receiving water (Raw wastewater).

The functional unit was 100 L of wastewater treated by the bioaugmented CW in one cycle. For non-bioaugmented CW, operational stage was considered during impact assessment. For the bioaugmented CW, operational stage and the stage of producing inocula were all taken into account for the assessment. For both CWs, input flows associated with energy resources (electricity for pump) were investigated, and output flows consisted of effluent discharge and gas emissions to air. The preparation, cultivation and subsequent process of inocula were included into the scope of bioaugmented CW, in which the chemical substances addition and energy resources associated with emissions to air were taken into account.

2.3.2. Inventory analysis

Tables 1 and 2 show the inventory data for the CWs and the inocula. Coal consumption accounted for the electricity to power equipment and facilities that were employed the experimental study. Carbon dioxide