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A systematic framework to assess the feasibility and effectiveness of carbohydrate-rich wastewater treatment with bioresource exploitation alternatives in small- and medium-sized enterprises

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ABSTRACT

A conceptual design framework for wastewater treatment with advanced bioresource exploitation is developed. Using the framework, a process that minimizes chemical oxygen demand (COD) of the treated wastewater is designed, considering factory-specific conditions while satisfying a constraint on treatment budget allowance (TBA). A food processing factory can now assess the initial investment, economic payback period, and environmental impacts associated with designs generated for various TBA constraints. For a specific factory in Taiwan producing 4900 kg day^{-1}of tofu, a baseline 1.9 million New Taiwan dollars investment is proposed, which is paid back in 5.5 years mainly by the avoided pollution fee rather than recovered heat and electricity. Two anaerobic digestion reactors (73.9 and 70.7 m^3) and a 5 kW biogas combined heat and power unit will reduce wastewater COD (from 14793 to 100 mg L^{-1}) and achieve a potential reduction of 72 kg–CO_2–eq. day^{-1} of greenhouse gas emissions.

1. Introduction

Achieving reductions of environmental loadings and maintaining economic competence are particularly challenging for small- and medium-sized enterprises (SMEs). For example, food-processing wastewater (FPW) from SMEs in urban areas imposes loadings on the environment because of its nontoxic, but extremely high, content of organic pollutants. In addition to increasing energy costs, SMEs face serious challenges in reducing such environmental loadings within limited budgets. Biological treatment processes that can simultaneously exploit energy in the form of biogas such as methane or hydrogen might solve both economic and environmental challenges for SMEs. However, wide implementation is hindered because each small factory has specific FPW characteristics, constraints, and allowance for initial investment, while available technologies and energy needs are diverse.

Here, we propose a design framework to leverage the implementation of treatment systems that can exploit urban energy from FPW. By using the framework, a conceptual design of a process system is generated considering: 1) performance and biochemical and physical characteristics of alternative treatment systems; 2) investment and maintenance costs and savings in operation costs; 3) reactor size (with investment cost and space limitations); 4) loads on the environment (i.e., greenhouse gas (GHG) emission and chemical oxygen demand (COD)); and 5) the uses of the energy produced. Compliance with current and future environmental standards and minimization of the treatment cost are assumed the dominant factors in decision-making by SMEs. A case study demonstrates how the proposed scheme deals with environmental standards and treatment cost by using the proposed framework.

2. Methods

The four steps in the proposed design framework for SMEs in the food-processing industry are presented in Fig. 1. Each step is explained in the following sections.

2.1. Process synthesis

A biological process system that utilizes FPW is designed to provide treatment and energy exploitation functions. First, from a pool of treatment processes, candidate processes are identified considering their compatibility with the characteristics of the FPW. Next, the constraints (e.g. the range in concentrations of inhibiting compounds) on the processes are understood to make sure that each unit process is workable in the integrated system. Finally, the

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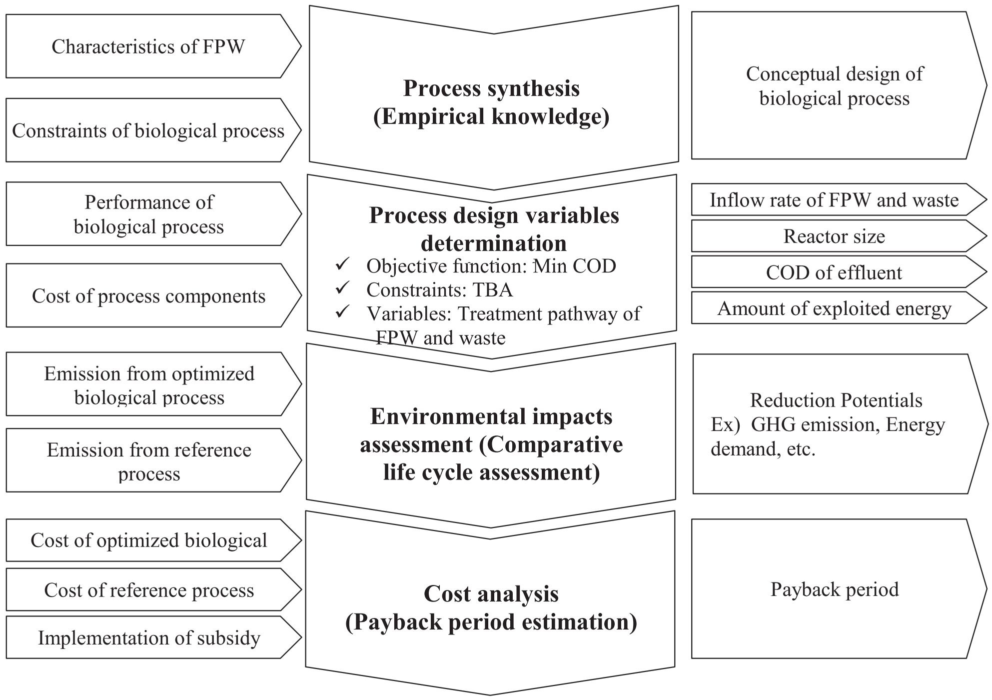

Fig. 1. The four steps in the proposed design framework for SMEs in the food-processing industry. (COD: chemical oxygen demand, FPW: food processing wastewater, GHG: greenhouse gas, SMEs: small- and medium-sized enterprises, TBA: treatment budget allowance).

candidate processes are integrated to form a conceptual model without design variables (e.g. reactor size, flow rates, operation conditions) determined.

2.2. Process design variables determination

In this step, process design variables are determined by minimizing the COD of the effluent (kg-COD day^{-1}). In some cases, including tofu factories, organic solid waste is generated together with FPW. This waste can be diluted and introduced to the FPW treatment processes to enhance the energy production. Therefore, cases with and without introduction of diluted waste are explored.

The performance of the constituent processes is highly dependent on the characteristics and quantity of the feedstock introduced to the reactors. We consider this by utilizing the relationships between the removal efficiency and loading rate of COD for the reactions chosen.

The design variables are subject to the treatment budget allowance (TBA) constraint: the sum of investment and operating costs may not exceed the TBA limit. The optimization is performed over a range of TBA values. In this way, we can provide factory owners with information on how the design of the process and its performance changes for the TBA they allocate. Energy conversion equipment is determined by the rate of generated gases and the forms of energy (e.g. heat, electric power) that are needed in the factory.

2.3. Environmental impact assessment

A framework for comparative life cycle assessment (LCA) of FPW treatment with energy exploitation opportunities is shown in Fig. 2. The process designed by minimizing the COD for a given TBA is evaluated in comparison with the set of reference processes chosen as a benchmark.

This framework assists in constructing appropriate system boundaries that include processes that provide equivalent functions. In both scenarios, FPW must eventually be treated to meet the environmental standards. When FPW is not treated in the factory, the municipal wastewater treatment plant (WWTP) is included in the system boundary. Furthermore, the environmental interventions from the entire life cycle require attention. In the proposed framework, environmental loads associated with: 1) energy exploitation and conversion; 2) FPW treatment; 3) production of other inputs to the process (e.g. NaOH and sludge); and 4) energy production at the regional power plant are accounted for. The food processing is omitted from the scope because the choice of treatment and recovery strategies does not affect the environmental loads in this part of the system. The functional units of the scenarios in this framework should be equivalent in both the treatment of the FPW and in the energy (i.e. electricity and heat) supply.

2.4. Cost analysis

The investment costs of the proposed treatment and conversion processes (I_{eval}) are paid back after some period if the operating costs (O_{eval}) are lower than those of the reference processes (O_{ref}). Lower operating costs are potentially achieved by the savings from the avoided fines and purchases of energy. Because treatment is performed on site, costs are reduced at the WWTP. A policy mechanism (e.g. subsidy, $S > 0$) may be implemented to redistribute these savings among the factories to promote distributed treatment processes. The payback period (PBP) is calculated with Eq. (1).

$$\mathrm{PBP} = \frac{I_{\mathrm{eval}}}{O_{\mathrm{ref}} - (O_{\mathrm{eval}} - S)} \tag{1}$$

3. Case study

Tofu wastewater and dregs are widely available as tofu is a very popular source of protein in the Asian diet. Here, a case study on a