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Development of a treatment system for molasses wastewater: The effects of cation inhibition on the anaerobic degradation process

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HIGHLIGHTS

- ▶ Anaerobic and aerobic combined system was used for treatment of molasses wastewater.
- ▶ The system showed high methane production efficiency and good effluent quality.
- ▶ It allowed treatment of high-strength wastewater in the range of 43–120 gCOD/L.
- ▶ Sulfur in the wastewater was removed as hydrogen sulfide by the anaerobic reactor.
- ▶ Cation inhibition level for anaerobic degradation process was determined.

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ABSTRACT

This study evaluated the process performance of a novel treatment system consisting of an acidification reactor, an upflow staged sludge bed (USSB) reactor, an upflow anaerobic sludge blanket reactor, and an aerobic trickling filter for the treatment of a high-strength molasses wastewater with a chemical oxygen demand (COD) of up to 120,000 mg/L. The USSB operating at 35 °C was capable of achieving an organic loading rate of 11 kgCOD/m^3 day with a methane recovery of 62.4% at an influent COD of 120,000 mg/L. The final effluent COD was 4520 mg/L. The system was effective with regard to nitrification and sulfur removal. Fifty percent inhibition of the bacterial activity of the retained sludge by the cations was determined at 8 gK/L for sucrose degradation, 16 gK/L for sulfate reduction, and 12 gK/L or 9 gNa/L for acetoclastic methane production. Cation inhibition of anaerobic degradation reduced the process performance of the USSB.

1. Introduction

Bio-ethanol production from agricultural feedstock has drawn increased attention as an alternative fuel in the context of increasing desire to reduce carbon dioxide emissions from the combustion of fossil fuels and increasing competition for the energy sources that are currently available. One of the main feedstocks for ethanol production is sugar cane, in the form of either cane juice or molasses, both of which originate in tropical and sub-tropical regions, such as Brazil, India, and Thailand (Wilkie et al., 2000; Pant and Adholeya, 2007; Sánchez and Carlos, 2008). Molasses-based distilleries produce large amounts of high-strength wastewater with high chemical oxygen demand (COD) values in the range of 80,000–130,000 mg/L (Tielbaard, 1992; Yeoh, 1997). The discharge of molasses-based wastewater without appropriate treatment can lead to the deterioration of aquatic environments. Baruah et al. (1993) reported that high biochemical oxygen demand (BOD) values of 25–490 mg/L (mean 200 mg/L) were detected at a distance of 8 km from the discharge point of a distillery facility in the river. An anaerobic pond process has been used to treat molasses-based wastewater (Nguyen and Gheewala, 2008), but this approach results in a loss of a potentially useful energy source and increases the emission of greenhouse gases, such as methane,

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from the pond. The development and dissemination of a sustainable treatment system is urgently needed, especially in developing countries.

Anaerobic treatment processes, such as upflow anaerobic sludge blanket (UASB), have been used to effectively and economically treat molasses-based wastewater. With a high organic removal efficiency and a relatively short hydraulic retention time (HRT), UASB reactors have high rates of biogas production, and the gas can be used as fuel in multiple facilities (Satyawali and Balakrishnan, 2008). Recently, an upflow staged sludge bed (USSB) equipped with multiple gas–solid separators (GSS) was successfully used in the treatment of molasses-based wastewater (Onodera et al., 2011). Quickly discharging the biogas produced on site to reduces the upflow velocity and allows the USSB reactor to operate by retaining large amounts of sludge (van Lier et al., 1994).

The performance of the reactor may be compromised by inhibitory inorganic constituents, such as sulfate and potassium, that are present in the molasses-based wastewater (Boopathy and Tilche, 1991; Wilkie et al., 2000). The activity of anaerobic microorganisms is inhibited by sulfides (Koster et al., 1986; Lens et al., 1998; Onodera et al., 2011) and cations (McCarty and McKinney, 1961; Chen et al., 2008). Although both cations and anions are present in salt solutions, the toxicity of salt is predominantly related to cations (McCarty and McKinney, 1961). Unlike organic substances and sulfate, the dilution of the influent by effluent recirculation does not reduce the cation concentrations in the treatment system. A freshwater dilution of the high-strength wastewater does reduce cation concentrations, but the quantities needed and the associated costs can make this approach prohibitive in some regions. A non-dilution or low-dilution system would be beneficial in the treatment of molasses-based wastewater. A quantitative evaluation of the effects of cation inhibition on anaerobic degradation is required to develop a stable process for the treatment of molasses-based wastewater.

Anaerobic reactors require a post-treatment process because their effluents still contain relatively high concentrations of organic substances. An activated sludge process is commonly used as a post-treatment process, as demonstrated by the development of a process to anaerobically treat distillery wastewater (Torrijos and Moletta, 1997; Satyawali and Balakrishnan, 2008). While activated sludge produces high-quality effluent, the high energy consumption and the high sludge production of this process are of concern. Wetland construction is another process that has been used to anaerobically treat molasses wastewater (Sohsalam and Sirianuntapiboon, 2008). Although a constructed wetland operates at low cost and has simple operational and maintenance requirements, a longer retention time is required to achieve a feasible effluent quality. In reviewing the advances in the biological and physico-chemical processes used in the treatment of molasses-based wastewater, Satyawali and Balakrishnan (2008) concluded that an improved process was urgently needed.

In this study, a combination of a UASB reactor and a down-flow hanging sponge (DHS) reactor, which is an aerobic trickling filter process using sponge as a medium, was evaluated for use as a post-treatment process. The UASB reactor was expected to remove the remaining organic substances and recover energy in the form of methane gas. The UASB reactor could also be effective as a reservoir for USSB sludge in the case of an unexpected sludge washout. With its simple operational and maintenance requirements, a DHS process can be used for residual organic removal and nitrification (Machdar et al., 2000). One of the advantages of the DHS process over conventional processes, such as the use of activated sludge, is the retention of a large amount of sludge inside the sponges, contributing to a high organic removal rate (Tandukar et al., 2006).

This study reports the development of a high-strength molasses-based wastewater treatment system consisting of an acidification reactor, a USSB reactor, a UASB reactor, and a DHS reactor. For high influent COD values of 43,000, 80,000, and 120,000 mg/L, the changes in process performance were measured using a continuous flow experiment. The removal characteristics of sulfur, nitrogen, and phosphate were monitored. Using bacterial activity measurements, the effect of cation inhibition on the anaerobic degradation of organic substances was quantitatively determined.

2. Methods

2.1. Characteristics of the wastewater

For this experiment, the influent wastewater was made with raw molasses. The raw molasses was obtained from a sugar factory in Kagoshima, Japan. The synthetic wastewaters were made by diluting raw molasses in tap water to adjust the wastewater quality before use. Sodium bicarbonate was mixed with the influent wastewater to adjust the alkalinity of the solution. A summary of the initial wastewater conditions for the four operating phases is shown in Table 1. The composition of the molasses wastewater (120,000 mgCOD/L) was 57,000 mg/L total BOD, 1700 mg/L total nitrogen, 750 mg/L total phosphorous, and 94,000 mgCOD/L sucrose (Onodera et al., 2011). A small amount of an anti-foam reagent (KM-70, Shin-Etsu Silicone, Japan) was used. The synthetic wastewater was kept at 14 °C using a cooler (201TCN, AS ONE, Japan). The synthetic wastewater was prepared once or twice a week.

2.2. System description and operating conditions

Fig. 1 illustrates a schematic diagram of the proposed treatment system, which consisted of an acidification reactor, a USSB reactor, a UASB reactor, and a two-stage DHS reactor. The cylindrical acidification reactor had a height of 0.42 m and a diameter of 0.50 m. The USSB reactor, equipped with three GSS, had a height of 0.68 m. The cylindrical UASB reactor had a height of 2.20 m and a diameter of 0.075 m. The liquid volumes of the acidification reactor, the USSB reactor, and the UASB reactor were 23.6, 13.4, and 8.8 L, respectively. These anaerobic reactors were temperature controlled at 35 °C. The USSB reactor was seeded with mesophilic granular sludge (volatile suspended solid (VSS)/total suspended solid (TSS) = 0.67, sludge volume index = 9 mL/gSS). The total volume of the seed sludge was 315 gVSS for the USSB reactor and 160 gVSS for the UASB reactor. The DHS reactor was constructed by tiling right-triangular prism polyurethane foam pieces (width, 0.03 m, and length, 0.2 m) onto both surfaces of a vertical plastic rectangular sheet (length: 1.65 m). For convenience, the working volume of the two-stage DHS reactor was assumed to be the sponge volume, 6.7 L. The DHS reactor was maintained at an ambient temperature of approximately 24–30 °C. The DHS reactor was supplied with air using an air pump at a flow rate of 3 L/min for artificial ventilation. The DHS reactor operation was initiated 54 days after the system start-up. The flow rates and the HRT of the system are given in Table 2.

Table 1
Summary of the initial wastewater conditions for the four operating phases.

Phase	1	2	3	4
Day	532–598	599–688	689–720	720–749
COD (mg/L)	43,000	80,000	120,000	120,000
Sulfate (mgSO_4/L)	1600	3000	4600	4600
$NaHCO_3$ (mg/L)	6000	12,000	18,000	24,000