Bioresource Technology 102 (2011) 10767–10771

Contents lists available at SciVerse ScienceDirect

Bioresource Technology

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

Short Communication

Enhancement on biodegradation and anaerobic digestion efficiency of activated sludge using a dual irradiation process

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ARTICLE INFO

Article history:
Received 4 June 2011
Received in revised form 3 September 2011
Accepted 5 September 2011
Available online 10 September 2011

Keywords:
Aerobic thermophilic irradiation pretreatment (ATIP)
Dual irradiation process
Anaerobic digestion
Activated sludge
Carbon felt fluidised-bed reactor

ABSTRACT

A dual irradiation process involving aerobic thermophilic irradiation pretreatment (ATIP) and intermittent irradiation anaerobic digestion was developed to improve the digestion of waste-activated sludge. First, the effect of ATIP on further anaerobic digestion of activated sludge in batch mode was investigated. When exposed to ATIP for 24 h, the digestion reactor gave the highest methane yield, removed the most dissolved organic carbon (DOC) and showed the most effective reduction of VS compared to other irradiation times. This process was further enhanced by using an anaerobic fluidised-bed reactor packed with carbon felt in semi-continuous mode for digesting the pretreated activated sludge under intermittent irradiation conditions. Dual irradiation for 24 h followed by 60 min of anaerobic irradiation processing per day turned out to be optimal. This resulted in 65.3% of VS reduction, 83.9% of DOC removal ratio and 538 ml/g-VS of methane yield.

1. Introduction

Increasing sludge production poses a large problem to communities and local wastewater treatment plant operators. Sludge is a useful bioresource, and its anaerobic digestion is of high interest. In wastewater treatment plants, the waste-activated sludge is known to be more difficult to digest. The rate-limiting stage for waste-activated sludge degradation is hydrolysis. There is a need to find more efficient pre-treatment in order to enhance the methane yield from anaerobic digestion. There are several pre-treatment options: mechanical, thermal, chemical or biological treatments (Weemase and Verstraete, 1998). The goal of each of these treatments is to increase the liquid fraction in order to make the sludge biomass more biodegradable. An alternative system is autothermal thermophilic aerobic digestion (ATAD) (Kelly et al., 1993). A modification of the ATAD system known as the dual digestion process uses an aerobic thermophilic pretreatment (ATP) prior to anaerobic digestion. In the first stage, sludge is "pretreated" through efficient solubilisation and partial digestion of the particulate organic matter. According to several authors, the optimal ATP temperature is around 170–200 °C (Li and Noike, 1992; Weemase and Verstraete, 1998; Bougrier et al., 2006). Thermally treating the waste around 175 °C, combined with anaerobic digestion, can highly reduce sludge production; this reduction can reach 50–70% depending on the specific process (Kepp et al., 1999; Graja et al., 2004). However, higher thermal treatment temperatures are associated with thermal losses, technological problems (pressure, materials, exchanger fouling), investment costs, maintenance costs and the cost of integrating this pretreatment into the whole wastewater treatment process. To optimise this system, a low-temperature, high efficiency thermal treatment process would be advantageous. Inactivation of pathogen bacteria such as *Escherichia coli* at a low temperature has been previously reported (Joyce et al., 1996; Aitken et al., 2007). The bacteria usually exist in waste-activated sludge and should be removed before re-usage of the waste-activated sludge (Borowski and Szopa, 2007). Previous study (Joyce et al., 1996) has shown that solar heat could completely inactivate large populations of the faecal indicator organism, *E. coli* in 7 h in highly turbid water as long as the water temperature reached at 55 °C. A recent study has also shown that pathogenic *E. coli* strain could be inactivated with batch tests at 50 and 55 °C and decimal reduction time for the heat-sensitive fractions was in the order of 10 min at 55 °C and ranged from approximately 1–3 h at 50 °C (Aitken et al., 2007). Results from these previous studies indicate temperature of 55 °C is good enough to solubilise the bacterial cells. Therefore, the temperature of the alternative pretreatment

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doi:10.1016/j.biortech.2011.09.018

process in this study was set to 55 °C and the process was combined with light irradiation to improve the hydrolysis effect.

Although most conventional anaerobic systems are operated under dark conditions, the use of the lighted upflow anaerobic sludge blanket (LUASB) method under mesophilic conditions has been studied (Sawayama et al., 1999). Photoenhancement by incandescent lighting of methane production from thermophilic anaerobic digestion was reported by Tada and Sawayama (Tada and Sawayama, 2004; Tada et al., 2005). Additionally, optimal illumination on a thermophilic anaerobic reactor plays an important role in activating methanogens for the photoenhancement of methane production (Yang et al., 2009). Until recently, few studies have been conducted of anaerobic digestion from activated sludge by light irradiation, especially optimum irradiation conditions using dual irradiation digestion technology. Studies investigating the potential effects of activated sludge by dual irradiation digestion are particularly valuable.

The objective of this work was to study the effects of combining aerobic thermophilic irradiation pretreatment (ATIP) and intermittent irradiation anaerobic digestion on increasing waste-activated sludge solubility and enhancing the methane yield. A microscopic study was conducted for the purposes of understanding the microbial community under different irradiation conditions.

2. Methods

2.1. Aerobic thermophilic irradiation pretreatment

Six glass conical flasks (500 ml) with stir bars were used as the ATIP reactors. An amount of 400 ml of waste-activated sludge was added to each reactor, sourced from a local wastewater treatment plant (Tsuchiura, Japan). The waste-activated sludge had a COD of 16,100 mg/l, DOC of 1420 mg/l, TS of 23,000 mg/l, VS of 12,800 mg/l and a pH of 6.85. The reactor was operated in batch mode with constant stirring, and the temperature was maintained at 55 °C using an incubator (IS 600, Yamato Scientific Co., Ltd, Tokyo, Japan). Reactors were routinely irradiated for 0 (control), 8, 24, 28, 32, and 48 h. The light reactors were irradiated by 60-W incandescent lamps (LW110 V/60 W, Mitsubishi Osram, Tokyo, Japan). They were placed 7 cm away from the incandescent lamps at a light intensity of 100 ± 10 μmol m^{-2} s^{-1}. The light intensity was measured with a light meter Li-250 (Li-COR, Lincoln, NE).

2.2. Batch anaerobic reactor operation

Six glass bottles (500 ml) with stir bars were used as the reactors. Each reactor was filled with 320 ml of ATIP waste-activated sludge that had been previously subjected to 0, 8, 24, 28, 32, 48 h of light irradiation. Then, 80 ml of thermophilic methanogenic sludge (20% w/w) from the cattle waste treatment plant (Kyoto, Japan) was added to each reactor. Flasks were evacuated with nitrogen gas to remove oxygen from the reactor. A 50 ml gas sampling syringe was connected to the reactors to measure biogas volume. Biogas volume and methane content were measured every day to calculate the methane volume. And the initial and final values of VS were measured to calculate VS removal. Methane yield defined as the methane volume per gram of VS removal is usually used to indicate the performance of the anaerobic digestion process. The value of methane yield was calculated from methane volume and VS removal. The reactor was operated in batch mode in the dark for 10 days, and the temperature was maintained at 55 °C using an incubator like the ATIP device.

2.3. Semi-continuous operation of anaerobic fluidised-bed reactors

Carbon felt has a high porosity and a high specific surface area, which makes it an excellent bed material for microbe immobilisation. Yang et al., 2004b, 2009 reported that using carbon felt as the bed material in anaerobic reactors induced high levels of organic waste degradation and provided an excellent colonisation matrix. Therefore, in this study, a highly efficient fluidised-bed reactor with carbon felt bed material was designed.

In this operation, two types of reactors were set up. Each contained carbon felt (Japan Carbon Company, Tokyo, Japan) for microbial immobilisation. Each reactor was a 500 ml glass vessel. Twenty pieces of carbon felt (1 × 1 × 0.5 cm) with the same working volume (about 2.5% v/v) were added to make a fluidised-bed reactor. First, 80 ml of thermophilic methanogenic sludge (20% w/w) from a cattle waste treatment plant (Kyoto, Japan) and then 320 ml of waste-activated sludge that was pretreated for 24 h (80% w/w) with the composition similar to previous batch tests was added to the reactor. One reactor was irradiated for 60 min/day, while the other reactor was kept in the dark. The light reactor was irradiated by 60-W incandescent lamps (LW110 V/60 W, Mitsubishi Osram, Tokyo, Japan) and was placed 7 cm away from the incandescent lamps at the light intensity of 100 ± 10 μmol m^{-2} s^{-1}. The light intensity was measured with a light meter Li-250 (Li-COR, Lincoln, NE). After naturalisation for 20 days, the reactor was operated in semi-continuous mode with a hydraulic retention time of 12 days and was maintained at 55 °C until day 51. The operating parameters were based on the previously reported conditions (Yang et al., 2009; Pandey et al., 2011). VS reduction and DOC removal were calculated after the start-up period of 15 days and then measured once per week at the time when the ATIP sludge organics were fed. Therefore, the methane yields were calculated from the data of biogas production, methane composition and VS reduction every week after the start-up 15 days.

2.4. Analyses

A portion of the reactor contents was sampled. The effluent was centrifuged at 10,000 rpm for 10 min to precipitate the microbes. The supernatant was analysed for dissolved organic carbon (DOC) by a TOC analyzer (TOC-5000A, Shimadzu, Kyoto, Japan). Biogas production and reactor pH were measured. The biogas composition was determined by gas chromatography (GC-8A, Shimadzu) with a thermal conductivity detector equipped with a steel Porapak Q column (Shinwakakou, Kyoto, Japan) at 90 °C. All samples were measured in triplicate.

Using scanning electron microscopy (SEM), we observed the microbes present in the bioreactors for three conditions: the microbes before pretreatment, after pretreatment and the microbes that immobilized on the carbon felt (SEM) (DS-720, Topcon, Tokyo, Japan). For both dark and light-irradiated conditions, three samples of the attached bed materials were taken out, and the cells were washed with buffer solution (pH 7.0). Samples were prepared for SEM according to Yang et al. (2004a).

3. Results and discussion

3.1. Batch digestion performance

Batch experiments were run to evaluate how ATIP affects anaerobic thermophilic digestion for different irradiation times. The DOC after ATIP, methane yield, VS reduction and DOC removal are shown in Table 1. The dual digestion batch process with 24 h of pretreatment was found to be the most effective in terms of methane yield, VS reduction and DOC removal ratio. Compared with