An Improved Biomass Waste Anaerobic Degradation Technology for Producing Bio-gas Energy and Bio-fertilizers

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ABSTRACT

Due to rapid population growth and economic development, solutions for sustainable energy harvesting and waste treatment are desperately needed. The U.S. alone generates over 250 million tons of municipal solid waste per year two-thirds of which is organic waste. However, most of this valuable energy resource is directly disposed through landfill and incineration by which enormous environmental damages have been inflicted. Little or no is managed by environmentally-friendly anaerobic bio-degradation technology, typically because the historical degradation technology is still too slow to be applied prevalently. To solve these dilemmas, an improved biomass waste anaerobic degradation technology is proposed in this study. It uses rapid aerobic composting as a pretreatment method to effectively break down the most complex compounds of biomass waste to readily bio-degradable products and so significantly speed up the anaerobic degradation process. Laboratory testing demonstrates that, on average, a sustainable biogas yield rate of 1.6 L/day/L of wet biomass can be achieved. It is two to three times rapider than that of the traditional technology. The study concludes this improved biomass waste anaerobic degradation technology can be widely adopted for fast delivery of renewable biogas energy and healthy fertilizer.

Introduction

As energy prices, populations, and levels of environmental pollution continue to rise worldwide, we are in desperate and immediate needs of sustainable energy harvesting and waste treatment solutions. Crucially, as estimated by the U.S. Environmental Protection Agency (EPA) (2009a) and Department of Energy (DOE) (2009), with less than 5% of the world's population, the U.S. ranks as the world's largest producer of solid waste and consumes 22% of the world's primary energy. In 2009, more than 250 million (M) tons of municipal solid waste (MSW) was generated (EPA, 2009a) two thirds of which is organic material. Organic MSW is well-known as free and valuable energy resource. However, only 7% of MSW is aerobically composted to produce fertilizers and little or no is managed by environmentally-friendly anaerobic bio-degradation technology (Haaren et al., 2010). Sustainable management of biomass waste as renewable energy resource becomes an important issue in the U.S.

In general, the state-of-the-art methods of organic MSW treatment include landfill, incineration, aerobic composting, and anaerobic digestion. However, the problem is, these technologies have adverse effects to environment, ecology, agriculture, and human health, or have not recycled useful materials, or are too slow to be adopted prevalently.

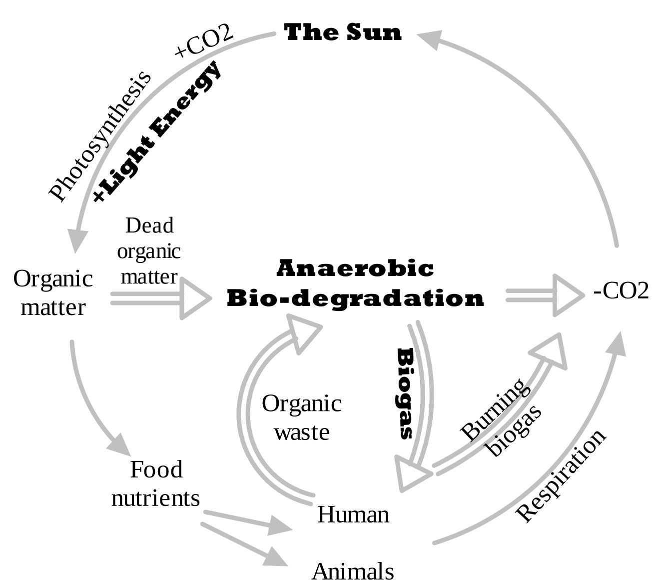
In the U.S., up to 54.3% of biomass MSW in 2009 was buried in the landfill (EPA, 2009a). As studied, 82% of surveyed landfill cells had leaks (LLSI, 2000). Consequent agricultural and ecological problems (e.g., soil compaction, erosion; low capability of defending storm water, aridity, and flood) and human health risks (e.g. cancer, birth defects, genetic mutations) are potentially serious. Globally, the rotted waste in the landfill continuously emits a significant source of methane, which is a potent greenhouse gas with 21 times the global warming potential of carbon dioxide (EPA, 2009b). Moreover, in many areas worldwide, landfill space is running out. A landfill shortage crisis is looming within the next 10 years.

Over one-fifth of biomass MSW in 2010 in the U.S. was also managed through the incineration (EPA, 2011). It uses thermal treatment at very high temperatures to wastes in specifically designed furnaces. The volume and weight of wastes can be reduced by 60 ~ 90% (Bridgewater and Lidgren, 1981). The incineration is falsely represented as an effective method of organic waste reduction. However, from an overall point of view, it provides little or no benefit to the entire biosphere that it changes the form of wastes into a variety of hazardous smoke, gases, and ashes. For instance, the highly toxic dioxins can cause acid rain which destroys vegetation, wildlife, rivers, soils, and architecture. The left harmful ashes from the incinerator are buried in the landfill and consequently exacerbate many forms of water pollution. Meanwhile, primary and secondary costs of the incineration are high and enormous energy and resources are utilized during constructions and operations.

Neither the landfill nor the incineration is a sustainable biomass waste management method that enormous environmental damages have been inflicted on water, air, and soil quality. On the contrary, aerobic composting is not merely an eco-friendly method to handle the waste by minimizing environmental effects but also delivers organic fertilizer for better agricultural productivity. Moreover, the composting conserves landfill space and reduces disposal cost. However, the traditional aerobic bio-degradation technology is too slow to be effective and used only to produce fertilizers. Recently, Li et al. (2012) developed a fast biomass waste aerobic degradation system for rapidly delivering fertile soils and also reclaiming bio-heat energy.

Actually, anaerobic bio-degradation by microorganisms in the absence of oxygen is also an eco-friendly method to break down the biomass waste and produce organic fertilizers. The energy end-product is biogas, which can be used for both heat and power.

Figure 1. Biogas energy generated during the anaerobic bio-degradation process



As shown in Figure 1, the most significant energy driven process on the Earth with respect to the ecosystems is that of photosynthesis. It converts light into a form of potential energy held in the chemical bonds of organic matter. After that, the natural biological process, anaerobic bio-degradation, transforms putrescible organic matter by microorganisms into H_2O and continuously releases the free fuel of biogas energy. However, the state-of-the-art biomass waste anaerobic bio-degradation technology still has several deficiencies that,

1. It is too slow to be effective that a large retention time of one to two months is needed with a production rate of about 0.3~1.0 L/day/L of wet biomass (Kloss, 1991; Raju and Ramaligaiah, 1997; Kashyap et al., 2003; El-Mashad and Zhang, 2010; Ferrer et al. 2010; etc.). The slower the rate of bio-degradation, the larger anaerobic digestion system, but the higher capital investment and the smaller energy and fertilizer production. Consequently, it causes restricted popularization of anaerobic bio-degradation technologies.
2. It primarily uses a single major source, e.g., animal (pig, cattle, sheep, goats, chicken or other poultry) manure, sewage sludge (AgSTAR 2008, Muhlbauer et al. 2009; etc.). However, massive and a variety of biomass wastes such as agricultural and industrial residues, municipal organic wastes, forest plantations, and natural forests as valuable renewable energy resources for the anaerobic bio-degradation have long been ignored.
3. Moreover, current various biomass pretreatment methods are often costly and problematic. For instance, high-intensity ultrasound (20~40 Hz), high pressures (600~2500 kPa) and heat treatments in a wide range of 50.0 ~270.0 ºC have commonly been adopted (Brooks, 1970; Vlyssides and Karlis, 2004; Jolis et al. 2004; Ferrer et al. 2006; De Silva, 2005; Roxburgh et al., 2005; Khanal et al., 2006; etc.) and regarded as relatively effective pretreatment methods.

Evidently, the high-intensity ultrasound and high pressure treatment processes using highly sophisticated devices are very costly and the thermal pretreatment also requires the input of a considerably amount of heat. It consumes a significant part of the produced biogas energy. Worth still, such methods can only disrupt relatively big particulate organic matter to small particles and so enhance the solubility of cell components to a certain extent. More cost-effective and efficient methods to fundamentally break down the most complex organic matter to readily biodegradable compounds and so speed up the bio-degradation process is highly needed to improve the technology.

An improved biomass waste anaerobic degradation technology is proposed in this study. An innovative pretreatment method using a speedy aerobic composting process (Li et al., 2012) is adopted to effectively break down multifarious biomass wastes to readily biodegradable products. It is a cost-effective pretreatment method that the aerobic composting system is made by cheap materials. Meanwhile, it only uses a small amount of ventilation and thermal heat (25~32 ºC) for supplying oxygen and enabling a "comfortable" environment for aerobic microbes. Moreover, the speedy aerobic composting system itself can reclaim free bio-heat energy. As studied, a sustainable heat flow rate of about 18.2 W/kg of wet biomass can be produced (Li et al., 2012). It is utilized as free heat resource during the fast anaerobic degradation process in this study.

To evaluate the improved biomass waste anaerobic degradation technology, a cylindrical anaerobic bio-degradation reactor together with the fast aerobic bio-degradation reactor and a biogas collector is used in the laboratory. Experimental results show that, on average, a sustainable biogas yield rate of 1.60 L/day/L of wet biomass can be achieved. It is two to three times rapider than that of the historically anaerobic degradation technology. Adopting this rapid and cost-effective biomass waste anaerobic degradation technology is promising that a variety of benefits can be achieved such as providing significant green renewable energy, improving the organic waste management, fast delivering healthy and fertile slurry, and minimizing the impacts of environmental pollution and human health.

The study begins of addressing system settings of the biomass waste anaerobic degradation technology. After that, experiments using various biomass wastes are conducted in the laboratory for the investigation. Experimental result reveals the innovative anaerobic degradation technology can effectively accelerate the process under the controlled conditions (e.g., aerobic composting pretreatment, moisture, temperature, etc.) to rapidly break down the organic wastes and produce free renewable biogas. The study concludes the improved biomass waste treatment technology is cost-effective and can be widely adopted for fast delivery of biogas energy and healthy fertilizer.

System Settings

As shown in Figure 2, the biomass waste anaerobic degradation system consists of three parts in the laboratory: a fast aerobic bio-degradation reactor (Li et al., 2012), a cylindrical anaerobic bio-degradation reactor, and a biogas collector.

Figure 2. System settings of the biomass waste anaerobic degradation technology

A fast aerobic bio-degradation reactor

A cylindrical anaerobic bio-degradation reactor

A biogas collector

The aerobic bio-degradation reactor can rapidly pretreat the biomass waste using mechanical ventilation with controlled supply air temperature and flow rates. The cylindrical prototype anaerobic reactor is developed using clear pipes with water seal at the top. The biogas collector is remained at a constant pressure condition for the convenience of data record and analysis.

Experimental Settings

Experiment settings for the biomass waste anaerobic degradation technology are specified in Table 1.

Pretreatment of the Biomass Waste Feedstock

Main components in the cell wall of organic matter are cellulose, half celluloses, pectin amylose, lignin, and various egg whites. Each type of organic matter has different content of these components, that is, the ability to resist settling and compaction of different organic waste is different. Thereby, as an essential element affecting the anaerobic biodegradation velocity, different types of biomass waste (e.g., grass clippings, leaves, sawdust, slurry) are mixed together first and then innovatively pretreated using the fast aerobic degradation reactor. It breaks down most complex organic matter to readily biodegradable compounds, directly bypasses hydrolysis stage, and so speeds up the anaerobic bio-degradation process. It also reduces the organic matter volume, destructs pathogenic organisms (outlet air temperature of the aerobic reactor is around 70.0 ~ 85.0 ºC), and stabilizes the feedstock for producing an energy-rich biogas in a fast and cost-effective manner.

Particularly, the fast aerobic degradation is a cost-effective pretreatment method that the aerobic composting system is made by cheap materials (e.g., PVC, wood, etc.). Meanwhile, it only uses a small amount of ventilation and thermal heat (25.0 ~ 32.0 ºC) for supplying oxygen and enabling a “comfortable” environment for aerobic microbes. Moreover, the speedy aerobic composting system itself can reclaim free bio-heat energy. As studied, a sustainable heat flow rate of about 18.2 W/kg of wet biomass can be produced and the outlet air temperate can be obtained around 70.0 ~ 85.0 ºC during this process. It is estimated that if only 80% of the produced heat is reclaimed through an air-to-water heat exchanger, adopting such an aerobic degradation system only with household biomass waste can adequately support daily domestic hot water needs in the U.S. (Li et al., 2012). Here, it is also utilized as free heat resource for the fast anaerobic degradation process.

In this study, a disposal capacity of 52.0 liter biomass waste on wet basis after the aerobic pretreatment is used in the fast anaerobic bio-degradation reactor.

Temperature

Temperature has a self-limiting effect on microbial activities and thus the rate of degradation of organic materials. There are three temperature ranges during which different types of microbes can be activated: psychrophilic at 5.0 ~ 15.0 ºC, mesophilic at 35.0 ~ 40.0 ºC, and thermophilic microbes at 50.0 ~ 55.0 ºC. However, anaerobes are most active in the mesophilic and thermophilic temperature ranges (Mital, 1996; Umetsu et al.,1992; Maurya et al., 1994; Takizawa et al., 1994; et al.).

A relatively high operating temperature has several benefits (Angelidaki and Ahring, 1994; Garba, 1996) including increasing solubility of organic compounds and growth rate of micro-organisms, enhancing biological and chemical reaction rates, and also increasing death rate of pathogens under thermophilic temperature range. However, on the other hand, since the microorganism are very sensitive to sudden thermal changes that the reaction failure even can be occurred at temperature changes in excess of 1.0 ºC/day. The control of high operating temperature for the thermophilic degradation is thus very sensitive as compared to the mesophilic degradation. Therefore, in this study, the temperature of the anaerobic reaction is designed in a range of 37.0~ 39.0 ºC.

Total Solid Contents

Water is essential to all living organisms, while biomass feedstock with a relatively high water content not only unnecessarily increases the digester volume, but also raises the heat input per liter of biomass waste required. It results in unfavorable process economics. On the other hand, high total solid contents (TSs) of biomass feedstock dramatically change the fluid dynamics of substrates and often cause process failure due to bad mixing behavior, solids sedimentation, clogging, and scum layer formation. Thus, to maintain a proper liquid rich condition, the TSs are stabilized in a range of 10~15% here.

PH Value

In addition, PH value is also an important parameter affecting the growth of microbes during the anaerobic degradation. It is obtained ranging from 6.5 to 7.5 in this study.

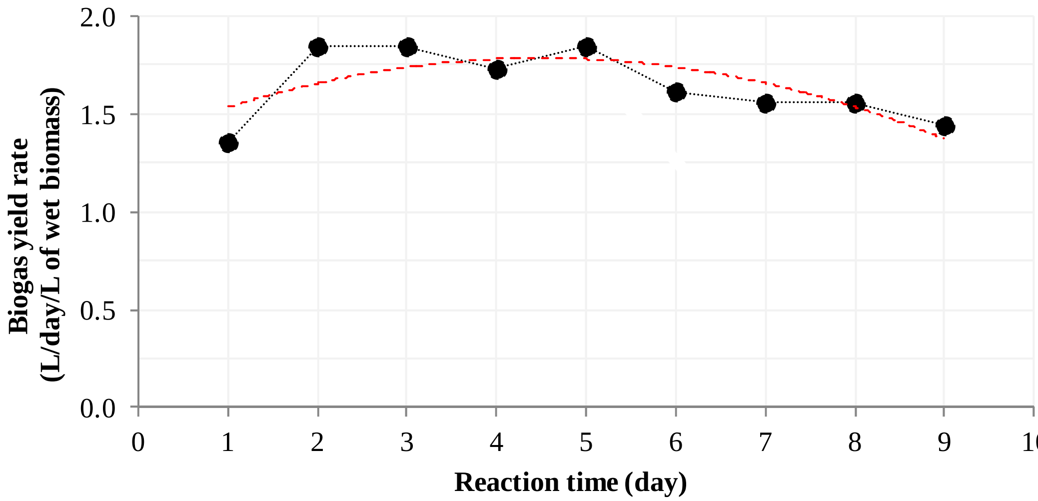
Table 1. Experimental design of the biomass waste anaerobic degradation system

Biomass Waste Feedstock		Operation Conditions		
Types of biomass waste	Total weight of wet biomass (L)	Total solid contents (%)	Temperature (ºC)	PH value
Grass clipping, leaves, sawdust, slurry	52.0	10~15%	37.0~39.0	6.5~7.5

Experimental Results

In the laboratory, the biogas yield rate and CH_4 and CO_2 concentrations of the biogas were sampled every 24 hours and plotted in Figure 3 to represent the corresponding experimental result. The horizontal axis is for reaction duration in days and the vertical axis is for biogas yield rate in liter per liter of wet biomass.

Figure 3. Experimental results of the fast anaerobic degradation technology



Observed from the acquired data, the reaction occurred fast and reached a biogas yield rate of 1.4 L/day/L of wet biomass within 24 hours. In the following 2~4 days, it rose to the peak biogas yield rate of 1.8 L/day/L. On average, it obtained a sustainable biogas yield rate of 1.6 L/day/L for at least 10 days with about 68~75% of CH_4 concentration and additional 24~30% of CO_2 content.

Currently, in most biogas power plants, a long retention time of about one to two months is needed with a production rate of only 0.3~0.6 L/day/L of wet biomass. The anaerobic degradation rate is still too low. A number of laboratory studies focusing on improving the bio-degradation rate are undertaken. As surveyed, about 0.6~1.0 L/day/L of biogas production rates can be achieved, while these studies conducted in the laboratory are mainly applied in little scale systems, e.g., 5~15 L of wet biomass reactors (Kloss, 1991; Raju and Ramaligaiah, 1997; Kashyap et al., 2003; El-Mashad and Zhang, 2010; Ferrer et al. 2010; etc.). Directly adopting such technologies can be problematic. The real performance in biogas power plants often cannot be guaranteed. The pretreatment methods using highly sophisticated devices in the laboratory also make the bio-degradation performance degraded significantly.

On the contrary, in our study, to ensure the scalability without sacrificing the bio-degradation performance and also lower the costs, we use large laboratory prototypes with different dimensions (50~100 L of wet biomass) and the cost-effective fast aerobic composting process as an effective pretreatment method. Currently, an optimal 1.6~1.8 L/day/L of biogas production rate can be obtained. It is about two to three times rapider than that of the historically anaerobic degradation technology. This demonstrates the improved biomass waste anaerobic degradation technology incorporating the energetic aerobic composting process can rapidly dispose biomass waste and reclaim free biogas energy.

Conclusions and Discussions

Owing to the ceaselessly rapid population growth and economic development, the demand of renewable energy and the amount of biomass waste generated worldwide, particularly in the U. S., have increased dramatically in the past 100 years. As valuable energy resources, the massive organic wastes have long been ignored and randomly buried in landfill or incinerated directly. However, neither the landfill nor the incineration is a sustainable biomass waste management method by which enormous environmental damages have been inflicted. On the other hand, the current anaerobic biodegradation technology is too slow to be applied prevalently and mainly relies on a single major source. Additionally, current biomass pretreatment methods are often problematic.

In this study, an improved biomass waste-to-renewable energy and -fertilizers technology is developed. A novel pretreatment method using the energetic aerobic composting processes to rapidly break down the most complex organic matter to readily biodegradable compounds is adopted. Laboratory testing with multiple types of biomass wastes is carefully conducted and demonstrates that, on average, a sustainable biogas yield rate of about 1.6 L/day/L of wet biomass can be achieved. Adopting this novel renewable energy technology will generate significant ecological, environmental, economic, and social benefits, such as:

1. *Rapidly producing renewable biogas energy and so decreasing the natural gas or electricity usage for heat and power,*
2. *Improving the organic waste management, saving the government financial expense for waste treatment,*
3. *Decreasing the dangerous air and water emissions which severely impact the environmental pollution and human health,*
4. *Fast delivering healthy and fertile slurry for agriculture and avoiding the extensive use of harmful chemical fertilizer and various insecticides.*

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