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Biogas energy production from tropical biomass wastes by anaerobic digestion

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HIGHLIGHTS

- Biogas energy yield of tropical biomass waste was evaluated.
- Liquid anaerobic digestion (L-AD) is effective for treating tropical food wastes.
- Solid-state anaerobic digestion (SS-AD) is suitable for treating albizia biomass.
- Albizia biomass showed higher methane yield than similar lignocellulosic biomass.

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ABSTRACT

Anaerobic digestion (AD) is an attractive technology in tropical regions for converting locally abundant biomass wastes into biogas which can be used to produce heat, electricity, and transportation fuels. However, investigations on AD of tropical forestry wastes, such as albizia biomass and food wastes, such as taro, papaya, and sweet potato, are limited. In this study, these tropical biomass wastes were evaluated for biogas production by liquid AD (L-AD) and/or solid-state AD (SS-AD), depending on feedstock characteristics. When albizia leaves and chips were used as feedstocks, L-AD had greater methane yields (161 and 113 L kg^{-1} VS, respectively) than SS-AD (156.8 and 59.6 L kg^{-1} VS, respectively), while SS-AD achieved 5-fold higher volumetric methane productivity than L-AD. Mono-digestion and co-digestion of taro skin, taro flesh, papaya, and sweet potato achieved methane yields from 345 to 411 L kg^{-1} VS, indicating the robustness of AD technology.

1. Introduction

Tropical regions have high biomass productivity compared to other regions (Parikka, 2004). Large amounts of biomass waste are generated each year from agricultural, forestry, and food systems in tropical regions, such as Eastern Africa (Ferrey, 2006; Otieno and Awange, 2006; Scheffran, 2010). *Albizia moluccana* (albizia) is one of the fastest growing tropical and subtropical trees (West, 2014), and is considered an invasive species on islands across the Pacific, such as Hawaii (EL Little and Skolmen, 1989). Taro, papaya, and sweet potato, which are native to tropical regions, are produced as traditional food (Manshardt, 2014; Midmore and Nguyen, 2003) and contribute large quantities of food wastes. For example, about 50% of the fresh papaya grown in Hawaii deteriorate and cannot be sold, creating waste that requires further treatment (Gill, 2004). As a result, there is an opportunity to improve the sustainability of energy production in tropical regions by converting these locally abundant biomass wastes into bioenergy products; however, potential technologies need to be evaluated.

Anaerobic digestion (AD) is a widely used technology that can process various kinds of organic wastes for biogas production by decomposing organic matter under oxygen-free conditions (Yu and Schanbacher, 2010). The biogas can be used to produce heat, electricity, compressed natural gas (CNG), and/or liquefied natural gas (LNG). The digestate, which contains nitrogen and phosphorus, can be used as a soil amendment. AD can be carried out at different total solids (TS) contents. Liquid AD (L-AD) is generally operated at a TS content of less than 15%, while solid-state AD (SS-AD) is usually operated at TS higher than 15%. High methane yields have been obtained in L-AD due to the good control of temperature, dilution of inhibitors, and good mass transfer provided by mixing. Compared to L-AD, SS-AD generally has higher volumetric methane

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productivity, fewer moving parts, lower energy requirements for heating and mixing, and an end product that is easier to handle. Floating and stratification of fats and fibers, a problem of L-AD, can be solved in SS-AD. The drawback of SS-AD is the lower methane yield than L-AD, which is caused by inadequate mass transfer in the system (Li et al., 2011).

AD of taro, papaya and sweet potato has been reported in several publications with methane yields ranging from 85 to 360 L kg^{-1} VS. Bindu and Ramasamy (2008) studied biogas production of taro from AD feeding with solid feedstock, and obtained CH_4 yields of 156–360 L kg^{-1} VS. Yang et al. (1984) reported CH_4 yields of 85–357 L kg^{-1} VS during AD of papaya processing wastes. Shiralipour and Smith (1984) investigated CH_4 production of different storage roots and average CH_4 yields about 330 L kg^{-1} VS were obtained.

The biogas yield of AD is substantially affected by the composition of the feedstocks (Ahn et al., 2010). Even for the same species of biomass, its composition can vary with the geographical location, variety, and harvesting season (Templeton et al., 2009). Therefore, characterization of feedstock components, such as cellulose, hemicellulose, lignin, and protein, is important for the estimation of methane yield.

To date, no reports on AD of albizia biomass nor on comparison between L-AD and SS-AD of tropical biomass wastes have been found. The objective of this study was to evaluate tropical biomass wastes, including albizia leaves, albizia chips, taro skin, taro flesh, papaya, and sweet potato, as feedstocks for biogas production by AD. The compositions of these feedstocks were analyzed. Both L-AD and SS-AD of these biomass wastes were conducted. Degradation of glucan and hemicellulose in albizia biomass during AD was also investigated.

2. Methods

2.1. Feedstock and inoculum

Albizia trees were cut from the United States Department of Agriculture (USDA), Agricultural Research Service (ARS), Daniel K Inouye (DKI) Pacific Basin Agricultural Research Center (PBARC) in Hilo, Hawaii. Branches containing leaves were trimmed and the main stem was shredded with a chipper/shredder with a grate size of 38 mm (Goossen CS1000 PTO Model, Harper, KS, USA). Removed leaves were shredded using a food processor (KitchenAid, St. Joseph, MI, USA), placed in plastic bags and frozen prior to shipment. Taro skin and cooked taro flesh were waste products collected from a local poi factory. Culled papaya fruits were taken from a local papaya packing house. Sweet potato tuberous roots were remnants collected from a field after harvest. The collected food wastes (taro, papaya, and sweet potato) were cut and processed in a food processor (KitchenAid, St. Joseph, MI, USA), stored in plastic bags, and completely frozen prior to shipment.

The processed feedstocks were shipped in cooler boxes with ice to the Ohio Agricultural Research and Development Center (Wooster, OH, USA) then stored at −20 °C (4 °C for albizia chips), and thawed before use. The following mixtures were prepared as feedstocks for co-digestion: taro skin/taro flesh (1:1, based on fresh weight); papaya/taro flesh (1:1, based on fresh weight); papaya/sweet potato (1:1, based on fresh weight); and taro skin/taro flesh/papaya/sweet potato (1:1:1:1, based on fresh weight).

Effluent from a mesophilic liquid anaerobic digester feeding with sewage sludge operated by Schmack Bioenergy (Akron, OH, USA) was used as inoculum for L-AD tests. The Schmack digester is a continuous stirred-tank reactor with a hydraulic retention time of 28 days. The effluent was centrifuged at 4000 rpm for 30 min to increase the total solids (TS) content from 7.6% to 17.7% for SS-AD tests. The inoculums were stored at 4 °C, and acclimated at 37 °C for 3 days before use. Feedstocks and inoculum samples were dried at 40 °C to reach a moisture content of lower than 10% (w/w) and then ground to 20-mesh prior to composition analysis.

2.2. Anaerobic digestion

L-AD lab-scale systems were set up by mixing the feedstock with inoculum to obtain a feedstock/effluent (F/E) ratio of 0.5 (based on volatile solids, VS), and adding tap water to obtain a TS content of 5%. L-AD trials were carried out in 1-L reactors, each of which contained about 800 g of mixed feedstock, inoculum, and water, and were sealed with a rubber stopper with an outlet for biogas collection. Reactors were placed on a shaker in a walk-in incubator, and incubated at 37 °C with orbital shaking at 100 rpm. Biogas generated was collected in 5-L Tedlar gas bags connected to the outlet of the reactor (CEL Scientific Tedlar gas bag, Santa Fe Springs, CA, USA). Biogas composition and volume were measured every 2 days (or longer during late periods of AD) for 24 days. Triplicate reactors were run at each condition. AD trials with only inoculum were also conducted as control.

Lab-scale SS-AD of albizia biomass was set up at an F/E ratio of 2.3 (based on VS) and a TS content of 20%. SS-AD trials were carried out with duplicate reactors at 37 °C for 50 days without agitation. Other conditions and operations were the same as those for L-AD.

After AD, the weight of digestate in each reactor was determined, and digestate samples were taken to determine TS. The rest of the digestate was dried and ground with the same method as used for the preparation of feedstock sample for composition analysis.

2.3. Analytical methods

The TS and VS were determined based on gravimetric analysis (APHA, 2005). Total carbon (TC) and total nitrogen (TN) were measured by an elemental analyzer (Vario Max CNS, Elementar Americas, Mt. Laurel, NJ, USA) to calculate the C/N ratio. Extractives were determined using the method reported by Sluiter et al. (2005). Crude protein contents were measured based on the method described by Hames et al. (2008). Crude lipids were analyzed by extraction from dry solids using Soxhlet extraction with hexane as solvent. Glucan, lignin, and hemicellulose were analyzed based on the NREL method (Sluiter et al., 2008). Briefly, extractive free biomass was hydrolyzed into monomers after a two-step acid hydrolysis, and the concentrations of these monomers were determined by HPLC (Shimadzu LC-20AB, Columbia, MD, USA). Acid-soluble lignin was measured by UV–Vis spectroscopy, and acid-insoluble lignin was determined by gravimetric analysis.

The volume of biogas collected in the Tedlar bags was measured by a drum-type gas meter (Ritter, TG 5, Bochum, Germany) at 25 °C and ambient pressure. The composition of biogas (CO_2, CH_4, N_2, and O_2) was analyzed by a gas chromatograph (GC) (HP 6890, Agilent Technologies, Wilmington, DE, USA) equipped with an alumina/KCl deactivation column (30 m × 0.53 mm × 10 mm) and a Thermal Conductivity Detector (TCD). Helium was used as a carrier gas at a flow rate of 5.2 mL/min. Temperatures of the injector, column, and detector were set at 150, 40, and 200 °C, respectively. The methane production contributed by inoculum was subtracted from the measured value of each treatment.

The performance of the AD process was evaluated using CH_4 yield and volumetric CH_4 productivity. The CH_4 yield (L kg^{-1} VS) was defined as the volume of CH_4 produced per VS of feedstock added. The volumetric CH_4 productivity (L L^{-1} d^{-1}) was defined as the volume of CH_4 produced per reactor volume per day.