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Generation of biogas from coffee-pulp and cow-dung co-digestion: Infrared studies of postcombustion emissions

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ABSTRACT

Biogas could be produced by the co-digestion of coffee-pulp and cow-dung mixture under solar radiation. Gas chromatography and FTIR spectroscopy were used to analyze the chemical compositions of the generated biogas and its postcombustion emissions. From the first month of co-digestion at mesophylic conditions, methane content in the biogas attains 50% of the yield. This content increased up to 60% and remained almost constant for at least 8 months of further digestion. The FTIR gas spectroscopy analysis revealed the presence of over 70 chemical compounds in the biogas generated after 4 months of co-digestion along with several compounds hazardous to environment and animal health like isocyanic acid, and bromomethane. Combustion emission of the biogas contained several components like CH_4, C_3H_8, CO, SO_2, HI, and probably Br_2 which are strongly harmful to human and animal health. Results presented in this work indicate that if the biogas is to be considered as a fuel, the conventional combustion technology has to be upgraded to prevent these hazardous emissions to the atmosphere.

1. Introduction

Global depletion of fossil fuels has led to the search for alternative sources of energy. Biomass has the largest potential and can only be considered as the best option for meeting the demand and insurance of future energy (biofuel) supply in a sustainable manner.

The biofuel production from renewable resources refers particularly to the lignocellulosic biomass/materials, as this makes up the majority of the cheap and abundant non-food materials available from the plants. Therefore, lignocellulosic feedstock can offer the potential to provide novel biofuels of the second generation [1].

The production of hydrogen, natural gas, bio-oils, biogas, alcohols and biodiesel from renewable biomass have been a major research topic around the world with a prospect to supplement petroleum fuels and reduce environmental pollution.

Methane production from a variety of biological wastes through anaerobic digestion technology is growing worldwide and is considered ideal in many ways due to its economic and environmental benefits [2–8]. Methane fermentation is the most efficient technology for energy generation from biomass in terms of energy output/input ratio (28.8 MJ/MJ) among all the technologies used for energy production through biological and thermochemical routes [9].

Use of agricultural biomass for biogas production has been increased in recent years. Agricultural biomass includes food based portion (oil and simple carbohydrates) of crops such as corn, sugarcane, and the non-food based portion of crops such as the leaves, stalks and coffee pulp and husk. Use of specific microorganisms for pretreatment of wastes further promises to increase the yield and stability of the biogas end products. In addition, the use of agro-industrial residues in bioprocesses helps to reduce environmental pollution [10,11].

Coffee is the second largest traded commodity in the world and generates large amounts of by-products and residues during processing. Industrial processing of coffee cherries is performed to separate coffee beans by removing shell and mucilaginous part. In wet industrial processes a large amount (about 29% dry-weight of the whole coffee berry) of coffee-pulp is produced as the first by-product. The organic components present in coffee-pulp include cellulose (63%), lignin (17%), proteins (11.5%), hemicelluloses (2.3%), tannins (1.80–8.56%), pectic substances (6.5%), reducing sugars (12.4%), non-reducing sugars (2.0%), caffeine (1.3%), chlorogenic acid (2.6%) and caffeic acid (1.6%) [12–14]. Coffee wastes and by-products produced during coffee berry processing constitute a source of severe contamination and pose serious environmental problems in coffee producing countries. Therefore, disposal of coffee pulp is becoming an emerging environmental problem worldwide due to its putrefaction. Due to anaerobic conditions of open pulp-storage or composting areas, an uncontrolled emission of

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methane (CH_4) and nitrous oxide (N_2O) from these places cannot be excluded [15–17]. Hence the utilization and management of coffee wastes in large-scale still remains a challenge worldwide due not only to the generation of earlier gases, but also for their high contents of caffeine, free phenols and tannins, which are known toxic agents for many biological processes [18].

Previous studies have confirmed that the content of toxic materials in coffee pulp can be minimized by microbial degradation [19,20]. To that effect, generation of bioproducts such as biogas has been established at small scale. On the other hand, anaerobic digestion of animal manure has been investigated extensively [21–23]. The use of cow-dung for biogas generation is well established [24]. However, the costs of cow-dung digesters are not favorable due to their relatively low biogas yield in comparison with several other types of organic wastes such as food wastes [22,23].

One of the approaches for improving cost-benefit of cow-dung digesters is to increase their biogas production rate by co-digestion with more biodegradable wastes as long as such wastes are available in the vicinity of dairy farms and the farm land can use the nutrients and salts of the wastes. Co-digestion of different materials may enhance the anaerobic digestion process due to better carbon and nutrient balance [25,26]. According to Mata-Alvarez et al. [27], digestion of more than one substrate in the same digester can generate positive synergism and added nutrients can support microbial growth. During mesophilic anaerobic co-digestion of cow-dung and fruit or vegetable wastes in a continuous stirred tank reactor (CSTR) in mesophylic conditions (35 °C), Callaghan et al. [28] have found that increasing the percentage of fruits and vegetable wastes from 20% to 50%, the methane yield raised from 230 L to 450 L per kilogram of added volatile-solids. Misi and Forster [29] have found that batch co-digestion of cow dung with molasses (50% on dry weight basis) at 35 °C increases the biogas yield from 60 L to 230 L per kilogram of added volatile-solids.

Cow-dung contains a considerable amount of bacteria but low amounts of cellulose, lignocellulose, lignin and other organic components which are essential for bacterial growth and for biogas production. On the other hand, though coffee pulp contains bacteria nutrients (cellulose, hemicellulose, proteins) in large amount, it needs high concentration of bacteria to first degrade the toxic components (such as tanins and phenols), and then to produce biogas. These facts suggest that the mixture of coffee-pulp/cow-dung would result in a synergetic effect leading to a high biogas production.

Therefore, the first objective of this investigation was to evaluate the feasibility of using coffee-pulp from Mexican coffee harvest for biomethanation and the possibility of improving biogas yield by co-digestion of coffee-pulp with cow-dung in mesophylic conditions (35–40 °C).

The content and purity of methane (CH_4) in produced biogas are of great importance. Purity is highly affected by the presence of contaminants in trace or higher quantities, whose nature depends on the source of production. The most common contaminants are hydrogen sulfide (H_2S) and other malodorous sulfur containing compounds (i.e., mercaptans, such as CH_3SH) coming from the anaerobic fermentation of proteins and other sulfur bearing organic molecules. Depending on the composition of fermented organic material, the content of H_2S in biogas can vary from 10 to 10^4 -ppmV. H_2S, besides its bad smell, is non-desirable in energy recovery process as it gets converted to highly corrosive and environmentally hazardous sulfur dioxide (SO_2) and sulfuric acid (H_2SO_4). Therefore, H_2S must be removed for any eventual utilization of biogas.

Ammonia (NH_3) is another common contaminant coming from the anaerobic digestion of nitrogen-bearing organic molecules, which is not only corrosive but also presents a health risk. However, its combustion only slightly increases the emission of nitrogen oxides (NO_x). On the other hand, siloxanes are a group of silicon (Si) bearing molecules found in landfill biogases. These compounds are considered to be the third most important contaminant. During combustion, siloxanes form glassy microcrystalline silica. The other reported components in biogas (O_2, N_2, CO_2, H_2O, Ar) are considered to be harmless.

The information on the complete biogas chemical composition is indispensable for determining the quality and quantities of combustible and hazardous components before using it as a fuel. However, to the best of our knowledge, a complete analysis of biogas composition using FTIR spectroscopy has not been reported in the literature. Thus, the second objective of this research was to perform a complete FTIR analysis of the biogas composition generated from coffee-pulp and cow-dung co-digestion in order to determine the presence of volatile compounds, which might have a potential corrosive or harmful effect on human or animal health.

On the other hand, combustion and emissions characteristics of produced biogases are scantly reported in the literature. In this article we report the results of a preliminary study on the composition of emissions from the combustion of biogas obtained from coffee-pulp/cow-dung co-digestion. This study was performed using a laboratory combustor combined with a FTIR gas spectrometer.

2. Material and methods

2.1. Collection and preparation of substrates

Cow-dung was collected from a dairy farm. The samples were scraped off the feed lanes and collected in a bucket. The samples were transported immediately to our laboratory and placed in the digesters. Coffee-pulp (comprising the skin and mesocarp of the coffee berry) was obtained directly from the pulping machine during the processing of coffee berries by wet process from Huitzilan de Serdan, a volcanic, semi-tropical region of Puebla, Mexico and transported to our laboratory in cotton sacks same day. The coffee pulp was dried for about 5 h (from 11:00 to 16:00) under solar radiation of about $1000 \pm 50\,W/m^2$ for 5 days to reduce its moisture content before the digestion. A coffee-pulp weight loss of 50% (±1%) was measured after this direct solar drying.

2.2. Anaerobic digestion tests

2.2.1. Preliminary experimental performances

To optimize the coffee-pulp/cow-dung ratio in the digesters, we performed some simple tests in small vessels with different weight ratios of coffee-pulp and cow-dung. The volume of the test vessels was 1 L, with a working volume of about 0.5 L. 400 g of biomass with cow-dung/coffee-pulp ratios 1/0, 1/0.5, 1/1, 1/2 and 0/1 incorporated into the test vessels along with 0.1 L of water. The test digesters were equipped with a tap connected to an external pipe which enabled the sampling of the exhausted biogas. These digesters were placed in an oven operating at ~35 °C and were shaken manually twice a day.

The produced biogas was characterized for its CH_4 content (vol.%) through gas chromatography every day for one month (see Supporting Information, Fig. 1S). The results of such analysis revealed that the methanation capacity is best in the mixture containing 40 wt% coffee-pulp, 40 wt% cow-dung and 20 wt% water.

2.2.2. Experimental design and reaction system

The three batch digesters (Fig. 1) were therefore designed and built as follows. Stainless steel cylindrical vessels were equipped for the digestion process with an air-tight lid. The vessels had a