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Research article

Technical and economic feasibility of a solar-bio-powered waste utilization and treatment system in Central America

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ABSTRACT

The purpose of this study was to implement and evaluate a pilot-scale and closed-loop system that synergistically combines solar thermal collector, anaerobic digester, and constructed treatment wetland to simultaneously treat and utilize organic wastes. The system utilizes 863 kg of mixed animal and food wastes to generate 263 MJ renewable energy, produced 28 kg nitrogen and phosphorus fertilizer, and reclaimed 550 kg water per day. The net revenue considering electricity and fertilizer was $2436 annually. The payback period for the system is estimated to be 17.8 years for a relatively dilute waste stream (i.e., 2% total solids). The implemented system has successfully demonstrated a self-efficient and flexible waste utilization and treatment system. It creates a win-win solution to satisfy the energy needs of the community and address environmental concerns of organic wastes disposal in the region.

1. Introduction

The agriculture sector, as the second largest industry in Central America, has contributed an average of 9.19% of the total Gross Domestic Product (GDP) of Costa Rica in past decades (EN, 2015). Agricultural and agro-industrial activities generate a vast amount of organic wastes, such as animal manure, pineapple residues, sugarcane bagasse, rice straw, and coffee residues. Combustion of dry residues (i.e., sugarcane bagasse) and land application of wet wastes (i.e., animal manure), which are the most often used disposal approaches, have unfavorable economic performance and produce greenhouse gas emissions and air and water pollution. However, these organic “wastes” rich in proteins and high-caloric carbohydrates, can be potential renewable resources for clean energy generation. Previous estimates suggest that approximately 600 MW electricity can be generated in Costa Rica from the agricultural residues each year (Coto, 2013). However, only 2.2 MW of electricity is currently generated from organic residues, which is merely 3% of the power capacity in Costa Rica (ICE, 2016; Kohlmann, 2016). Development and implementation of environmentally and economically friendly utilization systems to treat agricultural wastes would help rural communities in Central America alleviate negative environmental impacts of organic waste streams, increase access to affordable clean energy, and advance development of low emission and high efficiency waste treatment technologies.

Anaerobic digestion (AD) is a natural biological conversion process that is proven effective at converting wet organic wastes into biogas, producing clean electricity while also reducing many of the environmental concerns associated with waste disposal (AgStar, 2010). Based on its operating temperature, AD can be categorized into thermophilic and mesophilic digestion. The thermophilic digestion occurs at a temperature of around 50 °C, while the mesophilic digestion is at a temperature of approximately 35 °C. Numerous studies have demonstrated that thermophilic cultivation can enhance AD performance by shortening retention time and thus requiring smaller vessel sizes, improving odor control, eliminating pathogens, increasing biogas production, and reducing total solids in the waste streams (Aitken et al., 2005; Sharma et al., 2013; Suryawanshi et al., 2010; Zarkadas et al.,

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2015). However, thermophilic digestion requires a certain amount of thermal energy to maintain the temperature, which may lead to an unfavorable energy balance for small-scale operations, even in the tropical temperatures of Central America. In order to overcome this disadvantage, other renewable energy sources need to be used. Solar energy, an abundant renewable energy source in Central America, is an excellent candidate to combine with small-scale on-site AD systems.

Several solar thermal conversion technologies have been developed in the past decades, such as flat plate thermal collectors, evacuated-tube solar thermal collectors, parabolic trough systems, power tower systems, and dish solar systems (Siva Reddy et al., 2013). Among these designs, flat plate thermal collectors are simple and economic solar thermal collection systems that are capable of efficiently providing the heat to maintain culture temperature during AD (Alkhamis et al., 2000; EPA, 1978). Furthermore, flat plate thermal collectors are suitable for the tropics, since warm weather reduces heat loss and thus improves thermal efficiency. Integrating a simple solar collection method with AD technology leads to a closed-loop concept of simultaneous waste utilization and clean energy generation not only for rural Central America, but also for other remote communities around the world. In addition, the anaerobic digester can also play an important role of storing low-density and inconsistent solar energy (as heat) into a relatively dense and reliable biochemical energy source – methane (Zhong et al., 2015).

Even with the utilization and treatment of wastes provided by the combination of solar thermal collection and AD, the effluent from AD still has relatively high levels of chemical oxygen demand (COD) (more than 10,000 mg/L), and nutrients (e.g., approximately 1000 mg/L nitrogen and 200 mg/L phosphorus). Mechanical separation is widely adopted by AD operations to separate the effluent into liquid and solid digestates (Monlau et al., 2015). The solid digestate, which is rich in fiber and phosphorus, can be used as a fertilizer with enhanced nutrient retention in soils (Liedl et al., 2006). As for the liquid digestate, besides direct land application, further treatment to reclaim “clean” water for irrigation or process uses has attracted increasing attention (Carretier et al., 2015; Sanyal et al., 2015). Numerous studies have demonstrated that utilizing a constructed treatment wetland (CTW) to treat the liquid digestate is an economically and technically sound approach to reclaim the water (Denny, 1997; ITCR, 2003; Kadlec and Wallace, 2009; Ritter and Shirmohammadi, 2001). Free water surface (FWS) and subsurface (SS) are two typical CTW configurations. Compared to FWS-CTWs, SS-CTWs have advantages of ensuring intensive contact between the wastewater and microbial biofilms growing on the media (ITCR, 2003), thereby reducing footprint of the wetland necessary to achieve treatment goals. Vertical flow SS-CTW (VFSS-CTW) is more common for intermittent wastewater influents and, when surface fed, increase the aeration of the media (Kadlec and Wallace, 2009). Therefore, a VFSS-CTW was incorporated into the integrated utilization system to treat the liquid digestate.

The goal of this study was to develop and evaluate an integrated small-scale, closed-loop, solar-bio-powered waste utilization and waste treatment system to simultaneously generate renewable energy, produce fertilizer, and reclaim water. The specific objectives were to: 1) design and implement an integrated solar-bio-powered organic wastes utilization system in Costa Rica; and 2) evaluate technical and economic performance of the system.

2. Materials and methods

2.1. Feedstocks

Chicken litter and food waste were used as the feed for the study. The chicken litter was collected from the chicken farm at Fabio Baudrit Experiment Station. Food waste was transported from a nearby food processing facility. The wastes mainly consisted of non-commercial over-ripe or damaged vegetables and fruits such as cucumbers, peppers, avocado, papayas, pineapples, and tomatoes. The food wastes and chicken litter were mixed at an average ratio of 1:12 (dry mass basis) to prepare the feed. An average of 863 kg per day of the wet feed containing 1.93 kg of the dry food waste and 23.02 kg of the dry chicken litter was fed to the studied pilot system. A portion of the reclaimed water was used as the process water to maintain the total solids (TS) content of 2.2% in the feed. The characteristics of the feed are listed in Table 1.

2.2. Pilot system

The demonstration pilot system was installed at the University of Costa Rica (UCR) Fabio Baudrit Experiment Station located in Alajuela, Costa Rica (10°0′29.02″N, 84°15′57.35″W). The system includes a modified flat panel thermal collector, a thermophilic continuous stirred tank reactor (CSTR) digester, electricity generators, and a VFSS-CTW (Fig. 1). The modified flat plate solar thermal collector converts solar energy into thermal energy to heat the influent of anaerobic digester and maintain the digester at thermophilic condition. A methane biogas storage bag serves as the fuel storage for electricity generator. The solid effluent is composted. The liquid effluent is post-treated by the VFSS-CTW to reclaim the water. The pilot-scale system has been running for two and half years. Data collected between August 2015 and March 2016 were used for this study. The detailed individual unit operations are described as follows.

2.2.1. Solar thermal collection

The solar-thermal heating module consists of a circulation pump (Model UP 26-99 F from Grundfos), heat exchanger, and 36 m^2 of solar flat plate collector. Eighteen 2 m^2 thermal collectors (Termi-solar®) were installed in three parallel rows of six collectors each row (Fig. 2a). The average annual irradiance at the site is 10.2 MJ/m^2 (Wright, 2008). The collectors were installed facing South at a 10° angle. Aluminum bronze (90/10) coils are used as the heat tubes in the solar thermal collectors. Water is the heat transfer fluid. The heated water is then stored in a 3 m^3 hot water tank (Green tank in Fig. 2d). A hot-water pump (Model PB 351MA from Wilo) circulates the hot water to heat the digester and maintain the thermophilic temperature (45 °C) using a 40 m High-Density-Polyethylene (HDPE) tubing heat exchanger in the digester.

2.2.2. Thermophilic CSTR digestion unit

The thermophilic AD unit includes a digester, a feeding tank, and an effluent storage tank (Fig. 2c, d, f). All vessels are cylindrical tanks with flat bottoms made by HDPE. The effective volume of the digester is 20 m^3. The feeding and effluent storage tanks are 10 m^3 each. Organic wastes are mixed and ground by a mill (ICAFE®)

Table 1
Characteristics of the feed.[a]

	Mixture feed
TS (g/L)	22.00 ± 3.3
VS (g/L)	11.60 ± 1.33
COD (g/L)	37.99 ± 2.75
Total carbon (% TS)	36.40 ± 1.30
Total nitrogen (% TS)	4.50 ± 0.20
Total phosphorus (% TS)	1.20 ± 0.11
pH	5.49 ± 0.12

[a] Data are the average of three replicates with standard deviation.