Journal of Environmental Management 184 (2016) 371–379

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

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

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ARTICLE INFO

Article history:
Received 29 May 2016
Received in revised form
27 August 2016
Accepted 2 October 2016
Available online 11 October 2016

Keywords:
Solar thermal collector
Anaerobic digestion
Constructed treatment wetland
Reclaimed water
Methane

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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http://dx.doi.org/10.1016/j.jenvman.2016.10.007
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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.

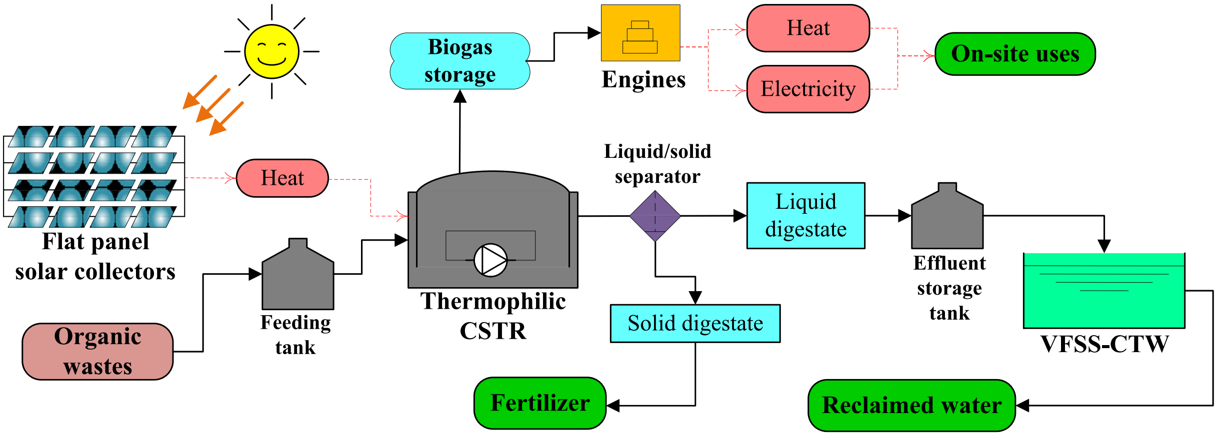


Fig. 1. Flowchart of the pilot solar-bio-powered wastes utilization system -: mass flow; **- -**: energy flow.

Fig. 2. The pilot system at Fabio Baudrit Agricultural Station a. Solar thermal collectors, b. Grinder, c. Feeding tank, d. Thermophilic CSTR and hot water tank, e. Liquid and solid separator, f. Liquid effluent tank, g. Biogas bag, h. Engines, i. VFSS-CTW.

before storage in the feeding tank. 863 kg of the feed with an organic loading of 0.50 kg VS/m^3 digester volume/day is pumped into the CSTR digester daily from the feeding tank. The average hydraulic retention time of the digestion is 20 days. A HDPE gas bag (60 m^3) is used for biogas storage. The biogas flow rate is measured using a biogas flowmeter (EKM-PGM 75) installed on the pipeline connecting the digester to the biogas bag. After digestion, a rotary liquid/solid separation unit (DESCAFE®) is used to separate liquid and solid digestates of the AD effluent (Fig. 2e). The semi-solid digestate is used as fertilizer for on-site crop applications. The liquid digestate is stored in the effluent storage tank and then fed to the VFSS-CTW by gravity.

2.2.3. *Control unit and data collection*

A data acquisition system (DAQ model CR1000 Campbell Scientific, Logan, UT) collects data from thermocouples (type K, probe ungrounded) every 20 s for the feedback control to maintain the digestion temperature as the ±2 °C of the set temperature (i.e., 46 °C). The DAQ sends a digital signal to power the hot-water pump if the digester temperature is lower than the set temperature. DAQ also records temperatures of the solar flat panels, hot water buffer, and storage tank every 5 min. In addition, the DAQ controls recirculation pumps for the VFSS-CTW operation.

2.2.4. *Electricity generator*

The electricity generation unit includes two 16 kW (Branco® B4T-5000 Bioflex, Brazil) biogas engines equipped with two activated carbon filters and a gas burner. The biogas flows from the gas storage trough the filters into the engines and burner. The electricity and heat generated from the engines and burner are consumed by on-site applications.

2.2.5. *VFSS-CTW*

A 7.6 cm diameter pipe is used to transfer the liquid digestate from the effluent storage tank to the VFSS-CTW by gravity to reclaim the water. The plants grown on the VFSS-CTW are: *Canna indica*, *Cyperus papyrus*, and *Iris graminea*. The dimensions of the VFSS-CTW are: 9 × 9 m of the bottom area, 12 × 12 m of the top area, and 1.1 m of the depth. The substrate media in the VFSS-CTW from bottom to top are: 0.2 m of stone (particle size of 12–20 mm), 0.2 m of pea gravel (particle size of 4–8 mm), and 0.7 m of coarse sand (particle size of 0.75–2 mm). A 2 m × 2 m geotextile membrane was installed beneath the discharge of the pipe to distribute the liquid digestate into the surface media as well as further remove TS in the liquid digestate. The TN loading of the VFSS-CTW was an average of 8.43 g TN/m^2 VFSS-CTW/day. A recirculation pump (Franklin Electric, model WS V52) is used to recirculate water from the bottom of the VFSS-CTW to the surface, and to enhance the performance of nutrient reduction. The recirculation distribution is

1.0 m above the sand surface and consists of a PVC network of 4 upright fire sprinkler nozzles obtained from a local hardware store (EPA, Alajuela, Costa Rica). The height of the recirculation spray was chosen to decrease interference of the redistribution spray by plants. The recirculation was carried out once per day from 2 am to 4 am.

2.3. Mass and energy balance analysis and economic assessment

Mass and energy balance analyses were carried out based on the data from the pilot operation during August 2015 to February 2016. The solar-bio-powered wastes utilization and treatment system was compared with a control anaerobic digestion system. The control system has the same unit operations of the solar-bio-powered waste utilization system except the solar thermal collection. A portion of biogas is required to maintain the temperature of the digester in the control system.

In addition to a technical robustness, economic performance is another important factor to determine the viability of the system. An economic assessment was then conducted for the pilot system. The capital expenditure (CapEx) and operational expenditure (OpEx) of the pilot operation were used for the economic assessment. Revenues include electricity offset and savings on fertilizer and irrigation water. The Modified Accelerated Cost Recovery System (MACRS) was used to calculate the annual depreciation of CapEx. In addition, an annual inflation of 3% was set for OpEx and revenues based on the five-year average inflation rate in Costa Rica. The net cash flow based on depreciated CapEx and inflated OpEx and revenues was conducted to determine the payback period. The parameters used for the economic assessment are described in Table 2.

A sensitivity analysis was carried out to elucidate the effects of unit operations on the payback period of the system. Three key parameters of solar collector area, TS of the feed, and wetland area were investigated. 25% of their base values was used to elucidate their impact on changes of the payback period.

2.4. Analytic methods

Feed characteristics were measured at the CIA (Agronomy Research Center, at the University of Costa Rica). Dry samples were used for chemical composition analysis of carbon and nitrogen. Total Solids (TS) and volatile solids (VS) were measured at the Fabio Baudrit Experimental Station following Hach method #8276. pH was measured on-site using a portable pH meter (Hanna Instruments 2211).

Liquid samples were taken weekly from different unit operations. COD (Hach method #8000), total solids (TS) and volatile solids (VS) (Hach method #8276) were measured at the Fabio Baudrit Experimental Station. Total phosphorus (TP) (method MAQA-1) and total nitrogen (TN) (method MAQA-40) were analyzed at CICA-LCA (Water Quality Laboratory at the Research Center of Environmental Pollution, University of Costa Rica).

Biogas samples were taken monthly using a sampling pump (SKC® Grab Air, Bag Sampler Cat. No. 222-2301) and stored in gas sampling bags. Bags were kept at 4 °C prior to the analysis at the CELEQ (Center for Research in Electrochemistry and Chemical Energy, University of Costa Rica). Methane and carbon dioxide contents in the biogas were quantified using a gas chromatographic method (Hewlett Packard® model HP6890 Plus) equipped with a thermal conductivity detector. The column was maintained at 250 °C and argon was used as carrier gas. The injected sample volume was 100 μL and the syringe was purged three times before injection.

Table 2
Parameters for economic assessment.

System components	Solar-bio-powered system	The control system without solar thermal collector
Feedstock	1000 kg per day with 2.1% TS	1000 kg per day with 2.1% TS
Food wastes	No cost	No cost
Chicken litter	No cost	No cost
Solar panel	36 m^2 solar panel	None
Anaerobic digester	20 m^3	20 m^3
Digester technology	Thermophilic digestion	Thermophilic digestion
Loading rate (m^3/day)	1	1
TS of the feed (g/L)	21	21
Retention time (day)	20	20
Reaction temperature (°C)	46	46
Biogas utilization		
Biogas engine	Two 16 kw engines	Two 16 kw engines
VFSS-CTW		
Area (m^2)	100	100
Labor cost		
Operator	20% of a full-time employee	20% of a full-time employee
Other expense		
Maintenance	Pumps, chemicals, and filters	Pumps, chemicals and filters
Bioenergy, water, and fertilizer		
Bioenergy	On-site electricity and refrigeration uses, compensating the energy demand	On-site electricity and refrigeration uses, compensating the energy demand
Fertilizer	On-site uses, compensating the fertilizer use	On-site uses, compensating the fertilizer uses
Water	Process uses	Process uses
Financial analysis		
Inflation rate	3% [a]	–
Depreciation	MACRS [b]	–

[a] The 5-year average local inflation at Costa Rica is used as the inflation rate.

[b] The depreciation period is set at 20 years. The depreciation is just on solar panel, anaerobic digester, and biogas utilization, and VFSS-CTW (the system installation cost is not included in depreciation). The annual depreciation rates from MARCRS (Modified Accelerated Cost Recovery System) are: 0.100, 0.188, 0.144, 0.115, 0.092, 0.074, 0.066, 0.066, 0.065, 0.065, 0.033, 0.033 (after 10 years).

3. Results and discussion

3.1. Solar-bio-powered wastes utilization system

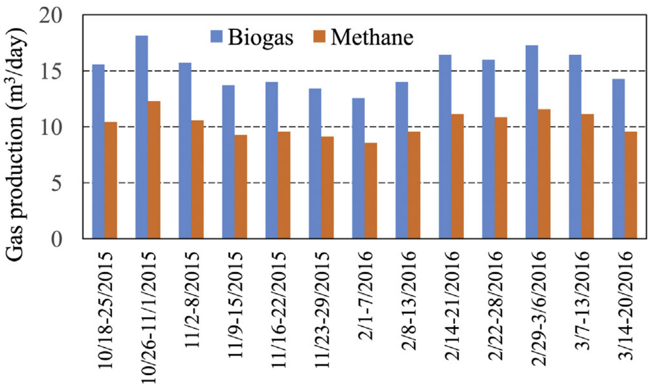
3.1.1. Solar-powered anaerobic digestion

Fig. 3 illustrates the performance of the pilot solar-powered anaerobic digestion unit during the experimental period. Average biogas production of 15.10 m^3 per day was achieved with a corresponding methane content of 68% (methane production of 10.21 m^3 per day) (Fig. 3A). The TS and VS were reduced to 0.99% and 0.47% in the AD effluent from 2.20% to 1.16% in the feed, respectively (Fig. 3B). The TS and VS removal of 55% and 59% were achieved by the thermophilic anaerobic digestion. Correspondingly, a methane productivity of 1.42 m^3/kg VS reduced was achieved. After liquid and solid separation, the TS in the liquid digestate is further reduced to 0.47%. The solid digestate has 15.96% TS and contains 2.62 g TN/kg TS and 31.03 g TP/kg TS, which was used as a fertilizer for on-site applications. The pH of the digestion was steady at 7.9 and no external pH adjustment was needed, even though the feed had a relatively low pH at 5.5. The pH of the liquid digestate after the liquid/solid separation was at 7.95. The strong buffer capacity of the digestion indicates that stable and robust anaerobic microbial communities have been established in the pilot system.

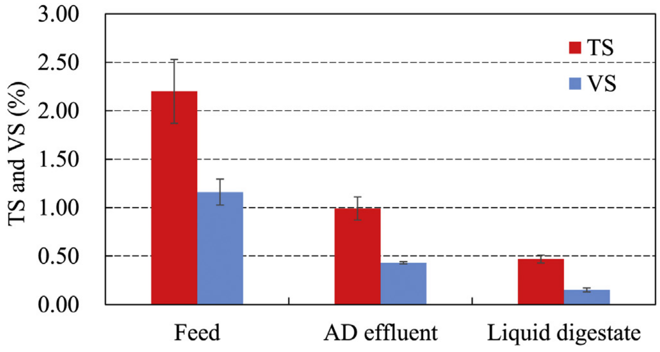
The temperature profile of the solar-powered anaerobic digestion demonstrates that the heat transfer fluid (water) in the solar thermal collectors can reach a peak temperature of 82 °C around noon. The solar thermal energy kept the temperature of the 5 m^3 thermal storage tank (hot water tank, Fig. 2d) in the range of 50–78 °C, which held enough thermal energy to maintain the digester at a consistent thermophilic temperature of 46 °C (Fig. 3C). The temperature profile clearly indicates that 36 m^2 is sufficient size for a solar collector to satisfy the thermal energy demand of a 20 m^3 thermophilic CSTR anaerobic digester in Costa Rica. Compared to solar-bio-powered systems in temperate region which still require biogas energy to maintain the digester temperature in winter months (Zhong et al., 2015), stable year-round solar radiation and temperature in tropical areas are certainly beneficial to simplify design and implementation of solar-bio-powered systems. Extra solar thermal capacity is not necessary and simple hot-water thermal storage is sufficient to satisfy the need of thermal energy demand, which significantly improve the system efficiency and reduce the capital cost.

3.1.2. VFSS-CTW treatment of liquid digestate

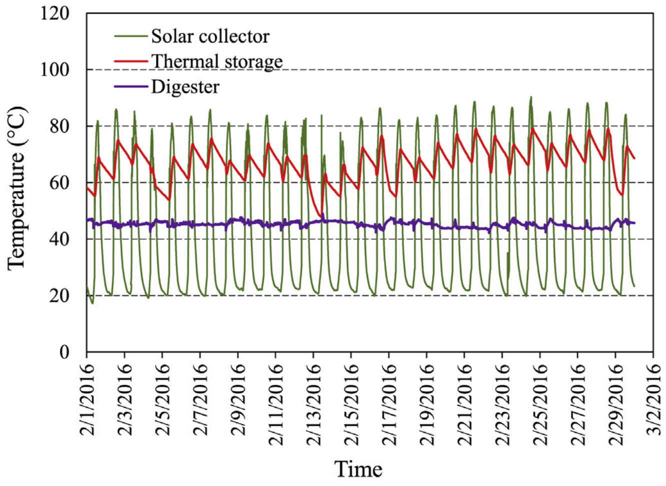
Even though the thermophilic anaerobic digestion converts a significant portion of VS into biogas, the liquid digestate from the digester still has very high nutrient contents. COD, TN and TP were 6,841, 1,078, and 106 mg/L, respectively (Table 3). The color of the liquid digestate is still black (Fig. 4). Additional treatment is needed to further reclaim the water for environmentally sustainable irrigation. The VFSS-CTW was used to carry out the task. The removal of COD, TN, and TP by the VFSS-CTW were 99%, 97%, and 99%, respectively. COD, TN and TP in the reclaimed water were reduced to 66.5, 34, and 0.8 mg/L, which satisfies the discharge standard in Costa Rica (COD < 150 mg/L, TN < 50 mg/L, and TP < 8 mg/L) (MINAE-MSP, 2007). Additionally, the VFSS-CTW significantly removed TS and VS to 0.54 and 0.17 g/L, and a clear water was correspondingly obtained (Fig. 4). Barros et al. reported that using a CTW to treat the effluent from an upflow anaerobic sludge blanket digester can reduce COD, TN, and TP from 466, 55, 3.76 mg/L in the effluent to 28, 37.5, and 2.8 mg/L in the reclaimed water, respectively (Barros et al., 2008). Comino et al. used a VFSS-CTW to treat the diluted effluent of a CSTR digester (Comino et al., 2013). The concentrations of COD, TN, and TP in the treated water were 194.5, 9.42, and 0.26 mg/L, respectively, with corresponding removal of 76%, 91%, and 80%. Our VFSS-CTW unit demonstrates comparable performance with these reports, even with substantially higher concentrations of influent nutrients, which indicates that the CTW is an efficient process to reclaim the water from the liquid digestate.



A. Daily gas production



B. Changes of total solids and volatile solids during the digestion



C. Temperature profile of the solar-powered anaerobic digestion

Fig. 3. Performance of the solar-powered anaerobic digestion $^{a, b}$. a. TS and pH data are from the weekly samples from August 2015 to March 2016. Biogas and methane data are collected from the weekly samples from October 2015 to March 2016 except the months of December 2015 and January 2016 due to the equipment maintenance. The bars are the average with standard deviation. The biogas volume was measured under the conditions of 1 atm and 45 °C. b. Temperature profile data are from the data-logger. The data in February 2016 were presented.

Table 3
Characteristics of the liquid digestate and reclaimed water before and after the VFSS-CTW.[a]

	Liquid digestate [b]	Reclaimed water [c]
COD (mg/L)	6841.25 ± 681.52	66.50 ± 12.86
TS (g/L)	4.40 ± 0.38	0.54 ± 0.06
VS (g/L)	1.46 ± 0.21	0.17 ± 0.04
TN (mg/L)	1028.33 ± 91.17	34.04 ± 8.55
TP (mg/L)	106.11 ± 16.34	0.80 ± 0.13

[a] The data are the average of three replicates with standard deviation.
[b] The liquid digestate in the effluent tank after liquid solid separation.
[c] The reclaimed water after the VFSS-CTW.

3.2. Mass and energy balance

The mass and energy balance analysis of the solar-bio-powered wastes utilization system were conducted based on the experimental data obtained from the pilot operation (Fig. 5 and Table 4).

With a HRT of 20 days, the AD reduced 48% of TS and correspondingly produced 14.56 kg biogas containing 6.13 kg methane and 8.43 kg carbon dioxide per day from 863 kg wet feed. Biogas was stored in a 60 m^3 gas bag for electricity and heat generation. After liquid and solid separation, 28 kg per day of semi-solid digestate containing phosphorus and nitrogen were produced, which was used as a fertilizer for crop farming at the Fabio Baudrit Experiment Station. The liquid digestate (820 kg) was further treated by the VFSS-CTW. 550 kg per day of the reclaimed water was generated and used for the on-site non-portable applications (Fig. 5).

The energy balance analysis further concluded that there was net energy output of the pilot solar-bio-powered system (Table 3). A system without solar thermal collector was used as the control for comparison. The heat required to heat the feed and maintain the thermophilic temperature of the 20 m^3 CSTR is 126 MJ/day. The electricity input is the electricity demand to power all equipment in the system including pumps, separator, and grinder (Table 3) and, in order to maintain a routine operation, 43 MJ/day of electricity is needed to fulfill these needs. The energy output from methane combustion is 306 MJ/day. Since the solar-bio-powered system uses the solar heat to maintain the digester temperature, no heat input is required. In contrast, the control system without solar thermal collector requires 126 MJ/day to maintain the thermophilic condition of the digestion. Therefore, the net energy of the solar-bio-powered system is 263 MJ/day, which is approximately twice as much energy as the control system without solar thermal collector generates (127 MJ/day) (Table 4). The energy balance clearly demonstrates an advantage of solar-bio-powered system.

According to the mass and energy balance analysis of the system, it is apparent that the energy efficiency is significantly enhanced by integrating solar thermal and AD technologies. Implementation of the solar-bio-powered wastes utilization and treatment system would also alleviate Greenhouse Gas emissions and ground/surface water contamination associated with current practices of organic residues handling in Costa Rica. For instance of the animal agriculture in Costa Rica, if all animal wastes (approximately 2,652,143 dry metric ton per year) from farm animals (Coto, 2013) are treated by the studied system, 856,377 metric tons of CH_4 could be captured, 623,253 metric tons of dry solid digestate (as fertilizer) can be produced, and a net energy of 37 petajoule (349 MW electricity, approximately 1.2 times more electricity than

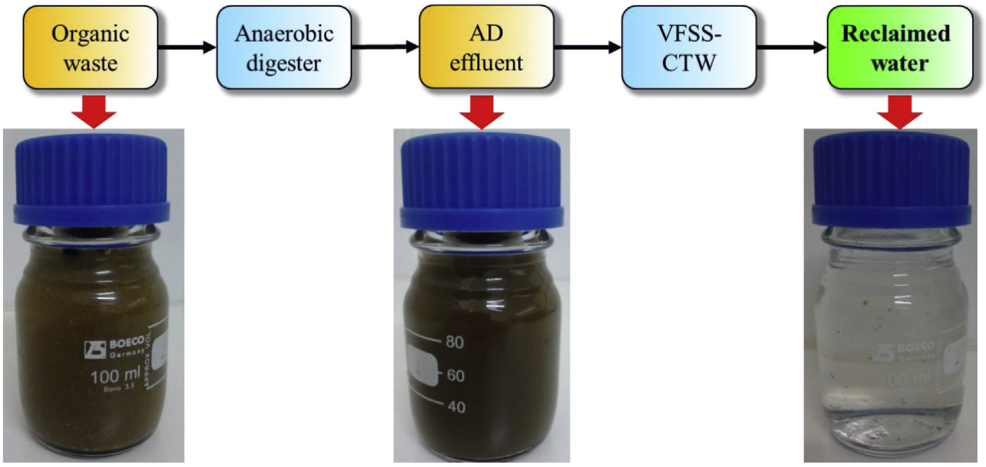


Fig. 4. Change of water quality during the process.

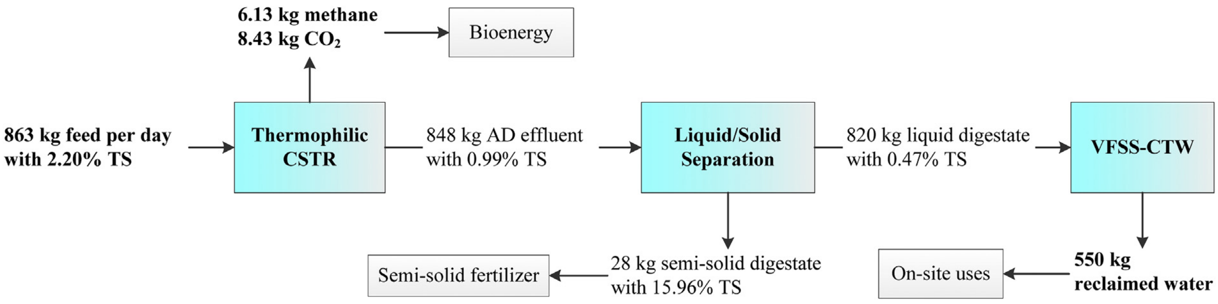


Fig. 5. Mass balance of the pilot system.

Table 4
Energy balance of the solar-bio-powered wastes utilization system.[a]

System	Solar-bio-powered system	The control system without solar thermal collector
Heat input (MJ/day) [b]	0.00	−126.00
Electricity input (MJ/day) [c]	−43.36	−43.36
Energy output (MJ/day) [d]	306.00	306.00
Net energy (MJ/day)	262.64	136.64

[a] The energy balance analysis was based on the mass balance and pilot operational data. Energy input is negative, and energy output is positive.

[b] The heat input was calculated by the heat equation. The amount of the feed per day is 1000 kg. The specific heat of the feed is 4.2 kJ/kg °C. The average temperature of the feed in Costa Rica is approximately 20 °C. The operational temperature of the thermophilic CSTR is 45 °C. Thirty percent of the heating energy for the feed is assumed to maintain the CSTR temperature at 45 °C.

[c] Daily average electrical consumption from weekly operation. Operating time (hours per week [h/wk]) for each equipment is distributed as: solar panels recirculation pump [56 h/wk, 124 W]; hot-water pump [20.3 h/wk, 350 W]; mixing pump in the digester [28 h/wk, 2238 W]; feeding pump [0.5 h/wk, 1492 W]; liquid/solid separator [0.8 h/wk, 746 W]; grinder [0.5 h/wk, 3730 W]; substrate pump [0.2 h/wk, 373 W]; effluent pump [0.8 h/wk, 373 W]; VFSS-CTW recirculation pump [10 h/wk, 373 W]; and mixing pump in the feeding tank [1 h/wk, 373 W].

[d] Since biogas is used for both heat and electricity generation, high heating value (55.5 MJ/kg methane) of the methane was used to calculate the energy output. The overall methane utilization efficiency was set at 90%.

current demand in Costa Rica) can be generated each year.

3.3. Economic assessment

Economic feasibility is another critical factor that determines commercial applicability of a technology. Therefore, an economic assessment was carried out to examine CapEx, OpEx, and revenue of the solar-bio-powered system. As it is presented in Table 5, the CapEx of the system implementation was $46,000. Among three unit operations of solar thermal collection, AD, and VFSS-CTW, the solar collector was the most expensive one ($13,500), followed by AD unit ($9000) and VFSS-CTW ($7000). The OpEx of the system ($3000) includes both maintenance and labor costs. Since the system is relatively simple and most of liquid transfer are automated, a worker spent approximately 20% of his time every day to feed and check the system. The labor cost is $2000 per year (based on wage rates in San Jose, Costa Rica). The maintenance cost ($1000) includes oil changes of pumps, chemicals for biogas clean-up, filters for engines, and replacements of some equipment. The revenues considered the energy offset from electricity and heat of methane combustion, and saving on fertilizer reduction. Under the

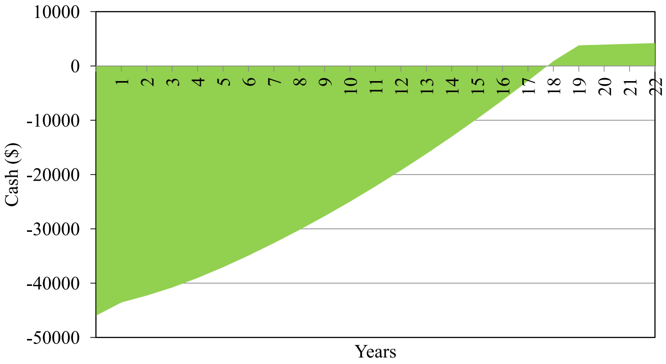


Fig. 6. The cash flow of the pilot solar-bio-powered waste utilization system under the current operational conditions.

Table 5
Economic analysis.

	Solar-bio-powered system	The control system without solar collector
Capital expenditure (CapEx)		
Solar unit	$13,500	–
Feeding unit (grinder and conveyor)	$2500	$2500
Anaerobic digestion unit (vessel and pump and gas meter)	$9000	$9000
Biogas utilization unit (gas bag and engines)	$4500	$4500
Liquid/solid separation (effluent tanks and separator)	$4500	$4500
VFSS-CTW (with pump)	$7000	$7000
System installation[a]	$5000	$5000
Total CapEx cost	**$46,000**	**$32,500**
Revenue		
Energy saving[b]	$5325/year	$2494/year
Water saving[c]		
Fertilizer[d]	$111/year	$111/year
Operational expenditure (OpEx)		
Maintenance	$1000/year	$1000/year
Labor cost[e]	$2000/year	$2000/year
Net Revenue		
Net revenue (only considering the revenue from the energy saving)	**$2436 per year**	**None**

[a] The cost of system installation is not included in the depreciation calculation.

[b] It includes the savings from both electricity and heat uses (such as heating the digester and absorption refrigeration). The energy cost is $0.20/kwh equivalent according to the utility price in Costa Rica.

[c] The reclaimed water was used to replace the demand of fresh water for dilution, washing, and other uses for the solar-bio-power waste utilization and treatment system. For the current operation, there is a minimum amount of the reclaimed water released from the system. The cost saving was not accounted into the calculation.

[d] The fertilizer cost was calculated based on nitrogen and phosphorus contents in the solid digestate. The nitrogen and phosphorus costs based on the commercial fertilizer were used for the calculation. The cost of nitrogen fertilizer is $0.95/kg nitrogen. The cost of fertilizer phosphorus is $2.12/kg phosphorus. The annual production of solid digestate (fertilizer) is 1631 kg TS with 0.31% P and 0.026% N.

[e] It is based on the current wage rate in San Jose, Costa Rica.

Table 6
Sensitivity analysis of key unit operations on the payback period of the pilot system.[a], [b], [c]

Unit operation	Key parameter	Values		Corresponding base cost for the unit operation ($)	Change on payback period (%) [d]
		Base value	Sensitivity range		
Solar collector	Collector arear (m^2)	36	18–54	13,500	±13
Anaerobic digestion	TS of the feed (%) [b]	2	1–3	5436	±51
Wetland	Wetland area (m^2) [c]	100	50–150	7000	±9

[a] All values are adjusted by ±25% of their base values.

[b] The biogas production is assumed to be proportionally changed with the TS change of the feed. The corresponding revenue from the energy saving is used as the base cost.

[c] The sensitivity analysis also assumes that wetland treatment would not be affected by changes in treatment area. Further analysis incorporating changes in treatment needs to be conducted to conclude more accurate results.

[d] The base payback period is 18 years.

current operation scale of 863 kg feed with 2.2% TS per day, the solar-bio-powered system can generate $5436 revenue per year from the energy and fertilizer savings. A net positive revenue of $2436 per year was realized compared to the negative revenue (-$395 per year) from the control system without solar thermal collector.

The cash flow analysis indicates that under the current operational conditions, the payback period of the pilot solar-bio-powered system is predicated to be 17.8 years (Fig. 6). A sensitivity analysis was further carried out to delineate the impacts of three key parameters (solar collector area, TS of the feed, and wetland area) on the payback period (Table 6). The results elucidate that TS of the feed is the most sensitive among the three parameters. 50% increase of the TS of the feed could increase the methane and fertilizer production to 15 m^3/day and 42 kg/day, respectively. The corresponding revenue is increased to $8154/year. The payback period can be reduced by 50% to 8.9 years. The second most sensitive parameter is the solar collector. Removing 50% of the collector area can shorten the payback period by 13%–15.5 years. The wetland area is the least sensitive parameter to influence the payback period. 50% of area reduction only causes a 9% change of the payback period. The sensitivity analysis clearly indicates that the economic impact of the wetland is not as big as other unit operations on the stand-alone system. However, considering the fact that ecotourism contributes to a large portion of Costa Rica's GDP, improper disposal or land application of the untreated liquid digestate negatively influences the ecotourism industry. Discussion on such impact is beyond the scope of work and was not included in this study.

According to the sensitivity analysis, several approaches can be adopted to improve the overall economic performance of the system. Increasing the TS content of the feed is certainly the first option to significantly increase the biogas production and reduce the payback period. Meanwhile, considering the fact that the current solar thermal energy exceeds the thermal need of the system (more collector area than needed) (Fig. 3C), reducing the collector area is the second option to improve the economic performance. Besides these two options, the third one could be the combination of TS increase and solar collector reduction. 50% increase of TS and 50% decrease of solar collector area could lead to a relatively short payback period of 7.7 years, which would greatly improve the economic performance of the system.

4. Conclusion

Integration of solar thermal conversion, AD, and CTW has been successfully implemented and evaluated. The system significantly improves the economic performance of organic waste management, and alleviates the environmental impact of the wastes. The concept has a great potential to be utilized by a wide range of waste management operations such as municipal wastewater and food waste handling. Essentially, the solar-bio-powered system turns an environmental and economic liability into a public and private asset, which would lead to extensive applications of AD, CTW, and solar technologies in Central America.

Acknowledgment

This research was supported by the U.S. Department of State West Hemisphere Affairs (S-LMAQM-11-GR-075). The authors would like to thank Michigan AgBioResearch for funding this work through faculty salaries. The authors would also like to acknowledge the assistance and support of the following laboratories at the University of Costa Rica: Agronomy Research Center (CIA), Water Quality Laboratory at the Research Center of Environmental Pollution (CICA-LCA), and Center for Research in Electrochemistry and Chemical Energy (CELEQ).

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