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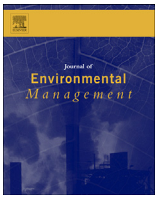

Research article

Costs and benefits of biogas recovery from communal anaerobic digesters treating domestic wastewater: Evidence from peri-urban Zambia

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ABSTRACT

Communal anaerobic digesters (ADs) have been promoted as a waste-to-energy strategy that can provide sanitation and clean energy co-benefits. However, little empirical evidence is available regarding the performance of such systems in field conditions. This study assesses the wastewater treatment efficiency, energy production, greenhouse gas (GHG) emissions, and financial costs and benefits of communal ADs used for domestic wastewater treatment in Zambia. Primary data on the technical performance of 15 ADs were collected over a 6-month period and in-person interviews were conducted with heads of 120 households. Findings from this study suggest that ADs offer comparable wastewater treatment efficiencies and greater GHG emission reduction benefits relative to conventional septic tanks (STs), with the greatest benefits in settings with reliable access to water, use of low efficiency solid fuels and with sufficient demand for biogas in proximity to supply. However, absent a mechanism to monetize additional benefits from biogas recovery, ADs in this context will not be a financially attractive investment relative to STs. Our financial analysis suggests that, under the conditions in this study, a carbon price of US$9 to $28 per tCO_2e is necessary for positive investment in ADs relative to STs. Findings from this study contribute empirical evidence on ADs as a sanitation and clean energy strategy, identify conditions under which the greatest benefits are likely to accrue and inform international climate efforts on the carbon price required to attract investment in emissions reduction projects such as ADs.

1. Introduction

Energy recovery from domestic wastewater has received increased attention in recent years as a strategy to reduce environmental impacts of wastewater treatment, provide alternative energy resources and offset operational costs of sanitation services (McCarty et al., 2011). New planning and design paradigms have been suggested to reorient wastewater treatment practices and objectives towards recovery of resources (Guest et al., 2009). This changing paradigm of waste as a resource rather than a costly problem creates opportunities for simultaneously addressing sanitation and energy challenges with a single approach. Both challenges are particularly pervasive in sub-Saharan Africa (SSA) where only 30% of the population has access to improved sanitation (WHO/UNICEF, 2015) and more than 80% use fuelwood as their primary energy source (Legros et al., 2009). Moreover, limited public financing for initial and recurrent costs of sanitation infrastructure, coupled with low willingness to pay for wastewater treatment, contribute to poor sanitation services in many low-income countries (Whittington et al., 2000).

Anaerobic digestion is one example of a process that can be used to simultaneously treat organic wastes and produce energy. As organic waste biologically degrades under anaerobic conditions, it is converted by various methane-producing bacteria to biogas through a series of biochemical steps (Rittman and McCarty, 2001).

List of abbreviations: AD, Anaerobic digester; CapEx, Capital expenditure; CH_4, Methane; COD, Chemical oxygen demand; CO_2, Carbon dioxide; CO_2e, Carbon dioxide equivalent; GHG, Greenhouse gas; FIB, Fecal indicator bacteria; MJ, Mega Joule; MPN, Most probable number; N_2, Nitrogen; NPV, Net present value; OpEx, Operational expenditure; PT, Public toilet; ST, Septic tank; SSA, Sub-Saharan Africa; SCC, Social cost of carbon.

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Biogas – primarily composed of methane (CH_4) and carbon dioxide (CO_2) – can be recovered and used as a clean, renewable energy source for cooking, lighting, generating heat and producing electricity. Typical organic substrates used in anaerobic digestion processes include livestock manure (Sasse et al., 1991), agricultural by-products and grasses (Nizami and Murphy, 2010), municipal organic wastes (Mata-Alvarez et al., 2003), domestic blackwater (Mang and Li, 2010) and municipal sewage sludge (Rittman and McCarty, 2001).

Anaerobic digestion technologies of varying complexity, arrangement and scale have been used throughout the world to treat organic wastes and generate energy. Large-scale anaerobic digesters (AD) are commonly used at centralized wastewater treatment plants in industrialized countries to treat sludge produced by municipal wastewater treatment, with recovered CH_4 generally converted to electricity (Rittman and McCarty, 2001). Various centralized anaerobic treatment technologies have also been used for the direct treatment of dilute, domestic wastewater in middle-income countries in tropical climates, particularly in Latin America (McCarty et al., 2011).

Household-scale ADs have also been used in rural areas of developing countries for domestic energy production, particularly in China and India where 43 million and 4.75 million, respectively, installations are estimated (REN21, 2016). In such installations, livestock manure is generally utilized as the organic substrate. Household-scale ADs operate based on similar anaerobic processes as large-scale systems, but are comparatively less complex, generally requiring no external energy inputs and limited monitoring of biological processes. Household facilities are also generally designed so that biogas can be used directly rather than converting it to electricity. Performance, costs and benefits of household agricultural ADs have been documented in the literature in a number of developing countries including China (Van Groenendaal and Gehua, 2010), Tanzania (Laramee and Davis, 2013), Rwanda (Bedi et al., 2015), Ethiopia (Mengistu et al., 2016) and Indonesia (Putra et al., 2017).

Comparatively fewer communal ADs have been implemented for the treatment of domestic wastewater at the community level (e.g. serving approximately 10-100 households) and correspondingly little information is available characterizing treatment performance, energy production or financial viability of ADs at this scale. The limited available literature on communal ADs includes analysis of biogas production from communal fixed-dome ADs treating household wastewater in India and Indonesia (Reynaud, 2014), biogas production and financial costs and benefits of small-scale upward-flow anaerobic sludge blanket septic tanks in Panama (Tilmans et al., 2014) and wastewater treatment efficiency and biogas production of tubular digesters treating blackwater in Haiti (Lansing et al., 2017). Through collection and analysis of primary data from communal ADs in Zambia, this study seeks to contribute empirical evidence on the costs and benefits of communal ADs used for domestic wastewater treatment and energy production. In particular, the study investigates (1) the technical performance of communal ADs in terms of treatment efficiency and biogas energy production, (2) the extent to and conditions under which biogas recovery may offset conventional energy use and greenhouse gas (GHG) emissions and (3) the financial viability of biogas energy recovery from domestic wastewater under a range of scenarios.

2. Methods

2.1. Study sites

The study was carried out in three low- to middle-income peri-urban communities in the southern African country of Zambia. The three communities—referred to hereafter as Site A, B and C—are located within the cities of Solwezi (Northwestern Province), Ndola (Copperbelt Province) and Livingstone (Southern Province), respectively. Primary data collection took place over a 6-month period from March–August 2015, spanning the warm/wet season (mean highs: 25–30 °C) to the cool/dry season (mean lows: 5–7 °C) (World Bank, 2012).

Recent sanitation upgrade projects were implemented in each of the three study sites during the period 2008–2012. The projects included installation of new household pour-flush toilets connected to small-bore sewer systems with communal ADs as primary wastewater treatment units. All study site ADs are fixed-dome digesters constructed with burnt bricks and cement plaster. Each has a nominal reactor volume ranging from 16 m^3 to 36 m^3. The ADs are integrated into the sewer network as interceptor tanks and therefore are located within each of the communities. Organic solids settle within the AD and undergo anaerobic digestion, while liquid-only effluent continues through the sewer network to secondary treatment systems. Biogas produced by waste decomposition is stored in the upper portion of the AD dome and is piped to nearby households where it is used as a cooking fuel. The sewer network and ADs have been operated by local water and sewerage utilities since 2012. In total, the study sites include 15 ADs, with each AD receiving wastewater from 9 to 67 households (Fig. 1 and Table 1). The term ‘inhabitant’ is used to denote an individual residing in the study site with a household toilet connection to an AD system. At Site C, one AD (denoted C-PT) also receives waste from a public toilet. No other organic waste is added to the ADs. On average across sites, biogas is recovered and piped to 6% of households with toilet connections (1–4 households from each AD) as biogas produced from domestic wastewater will provide only a fraction of a household's cooking energy requirements.

2.2. Data collection

2.2.1. Biogas use, production and losses

Biogas use and production was monitored using diaphragm gas meters (G4 200, Elster Group, Germany) and pulse data loggers (UX90-001, Onset Computer Corporation; Bourne, MA). Gas meters, with attached loggers, were permanently installed at all fifteen ADs throughout the 6-month study period. Biogas use was recorded on an hourly basis over the entire 6-month study period *via* the connected data loggers. Biogas production was measured at approximately monthly intervals between March–August 2015 *via* controlled release of gas over a 48-h period. Each device was positioned so as to avoid interfering with the household's cooking activities. Biogas losses were calculated as the difference between mean biogas production and measured biogas use per 24-h period.

2.2.2. Wastewater treatment performance

Wastewater treatment performance was assessed by evaluating reduction in (1) chemical oxygen demand (COD) (mg/L) and (2) fecal indicator bacteria (FIB) (CFU/100 mL). Data related to wastewater treatment were collected at only 13 of the 15 ADs because inflow pipes at 2 digesters were below water level thus preventing influent measurement. At each AD, COD measurements were taken six to eight times (March–August 2015) and quantification of FIB took place three times (June–August 2015), each at approximately monthly intervals.

2.2.2.1. Chemical oxygen demand (COD). COD reduction efficiency is calculated as (Equation (1)):