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Alternative co-digestion scenarios for efficient fixed-dome reactor biomethanation processes

Ioannis A. Fotidis*, Tiago Filipe Vicente Costa Laranjeiro, Irini Angelidaki

Department of Environmental Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark

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ABSTRACT

Many of the existing low-tech biogas reactors in the remote rural areas of developing countries have been abandoned due to the lack of substrates. This study investigated if unutilized biomasses are able to support an efficient biomethanation process with low carbon footprint, in these rural areas where low-tech reactors have been abandoned. Thus, the aims of this study were: a) to identify and evaluate alternative biomasses as anaerobic digestion substrates at a remote rural area site in India; b) to propose an efficient continuous biomethanation scenario for low-tech reactors; c) to assess the influence of the operational parameters on the stability of the anaerobic digestion process. The highest methane yield (137–159 NmL CH_4 L^{-1}) and co-digestion synergy (>20% more CH_4 than expected) were achieved by co-digestion of wastewater, cow manure, banana and rice by-products at 79.3/4.2/16.3/0.2 ww^{-1} VS ratio, respectively. Three fixed-dome reactors, R_{30}, R_{45} and R_{60}, fed with all substrates, operated with hydraulic retention times of 30, 45, and 60 days and organic loading rates of 2.18, 1.46, and 1.09 g VS L^{-1} d^{-1}, respectively (different co-digestion scenarios). R_{60} was the best continuous co-digestion scenario with 45% and 13% higher energy recovery from biomasses' utilization and 69% and 25% less greenhouse gas (GHG) emissions, compared to R_{30} and R_{45}, respectively. These results indicate that it is possible to operate efficiently low-tech biogas reactors with utilized biomasses as anaerobic digestion substrates.

1. Introduction

Emerging economies (e.g. China and India) are becoming major players in energy consumption, with increasing imports of oil and coal (IEA, 2013). Nevertheless, approximately 24% of the population in developing countries does not have access to electricity, and 49% still relies on traditional uses of biomass to cover their basic energy needs such as heating and cooking (IEA, 2011). Most of these people are located in rural areas (Cozzi, 2011). It is estimated that 80% of the total energy consumed in rural areas of India comes from sources such as livestock dung, firewood and crop by-products (Rao et al., 2010). This low energy availability in the rural areas of developing countries is triggering the quest for indigenous, accessible and renewable energy sources. Biomass-related technologies have attracted interest due to the relatively low production cost and low environmental impacts associated with them as well as due to the abundance and availability of substrates needed to produce them (Purohit, 2009). In addition, these technologies could be combined with sanitation development and reduction of greenhouse gas (GHG) emissions, which are additional worrisome issues in these areas (Dedinec et al., 2015).

Anaerobic digestion (AD) process could be a good candidate to fulfill the basic domestic energy needs of the inhabitants in these remote areas without the negative implications of the conventional biomass-related technologies (e.g. GHG and other emissions). AD is a microbially catalyzed process that allows the valorization of organic waste by the production of a high-energy content gas (biogas) and a liquid by-product (digestate) with high fertilizing value (Alburquerque et al., 2012; Roubík et al., 2016).

Biogas based, clean cooking systems are becoming more popular in Asian rural areas (Banerjee et al., 2016). Experience from previous projects in rural areas has shown that when biogas was produced in low-tech reactors (e.g. fixed-dome, floating cover and balloon or tube digester), could successfully be collected and used for cooking and lighting; eliminating the need for other energy sources (e.g. firewood, dried manure, etc.) (Bond and Templeton, 2011). The low-tech biogas reactors used in developing countries, have different configurations but are often compact, underground structures, typically with an inlet mixing chamber, an expansion chamber or outlet tank, and a gas collection exit on the top.

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* Corresponding author. Tel.: +45 45251418; fax: +45 45933850.
E-mail address: ioanf@env.dtu.dk (I.A. Fotidis).

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Furthermore, they often don't incorporate mixing or heating systems and have limited handling requirements (Tilley et al., 2014). Fixed-dome reactors are the most cost-effective type among all the small capacity reactors (1–6 m^3 working volume), based on the installation cost, the operational cost and the payback period (Singh and Sooch, 2004).

According to Cheng et al. (2014), the technical weaknesses and consecutively the inefficient operation for small capacity reactors, derives from: the structural components, the biogas utilization equipment, the biogas distribution systems, the digestate disposal, the operators' training and the biogas production. These six problems have been assessed by many researchers (e.g. Chang et al., 2011; Jha et al., 2012; Sovacool et al., 2015; Suzuki, 2015; Thien Thu et al., 2012) and practical solutions have been proposed. However, even though these technical issues can be solved, there are still many cases where the users abandoned their reactors due to the absence of available biomasses (Mwirigi et al., 2014; Pérez et al., 2014). Specifically, it has been reported that the basic operational problem of low-tech reactors is the availability and/or seasonality of the substrates (Ullah et al., 2015). Furthermore, in these close, remote societies, almost every available biomass resource is being exploited to the maximum extent, which makes it difficult to find substrates that will be provided willingly by the inhabitants. Thus, because conventional co-substrates are scarce, and since usage of energy crops is not an option, alternative co-substrates for manure-based biogas production, need to be identified.

Organic agricultural by-products of these rural areas could provide the solution to this problem. A good example of an unused by-product is the rice husk (a by-product of the rice milling process), which is mainly disposed in the developing countries through dumping in open fields followed by burning (Pode, 2016). This process contributes significantly to GHG emissions, reduces the productivity of the nearby lands, and causes air pollution from smoke and particulate matter emissions. The results of this disposal method are posing a direct health risk to people living near the dumpsites with potential skin, nose and eye irritation, decreased lung function and lung disease as asbestos-like silica fibers are released in the process (Bohra et al., 2013). The potential use of these types of by-products as substrates in low-tech biogas reactors could limit the problems that conventional disposal methods cause. Another important aspect especially relevant for the low-tech reactors, is the uncontrolled methane emissions from the outlet storage of the digestate (residual methane potential), that could generate high GHG emissions (Seppälä et al., 2013).

Today, there are more than 3.7 million biogas plants in India (Rao et al., 2010) and many of these are located in remote rural areas and have been abandoned due to the absence of the necessary amounts of substrate. Therefore, the objective of the current study was to investigate if in the remote rural areas, where low-tech reactors have been shut down, there are the available organic by-products able to support an efficient AD process with low carbon footprint. Therefore, Jyot Sujan, a small village with 1800 inhabitants composing 250 households, located in West Bengal jungle (India) with no access to domestic electricity, was chosen as a representative case study site of these remote areas. The village has eight fixed-dome reactors constructed in 2003 by the local government. All the reactors have been abundant for more than five years because their users claim lack of available substrates (Fig. S1, Supplementary data). Notably, all cooking energy requirements at the study site are met today by burning dried cow dung.

Based on the above, three aims were addressed in the current research. First, to identify available substrates in this remote rural area site and determine their mono- and co-digestion biological methane potentials (BMP). Second, to assess the continuous utilization of the available substrates in lab-scale, fixed-dome reactors. Third, to evaluate the influence of the operational parameters on methane production and residual methane potential of the digestate.

2. Materials and methods

The BMP of the mono and co-digested substrates were assessed through two experimental series, denoted “BMP assay-I” for mono-substrates, and “BMP assay-II” for co-digested substrates. Subsequently, the most promising co-digestion mixture was used in mesophilic (37 ± 1 °C) fixed-dome continuous reactor experimental series testing three co-digestion scenarios. Finally, the maximum residual methane potential was determined for each one of the three fixed-dome reactors.

2.1. Inocula

Two different thermophilic (53 ± 1 °C) methanogenic inocula derived from Snertinge centralized biogas plant (Denmark) were used in BMP assays I and II. The inocula were placed in an incubator for seven days to degas prior to use. The three fixed-dome reactors were inoculated with mesophilic (37 ± 1 °C) inoculum derived from Hashøj biogas plant, Denmark. The basic characteristics of the inocula used in the BMP and fixed dome reactor assays are presented in Table 1.

2.2. Substrates

Four different available AD substrates were identified in the study site. Specifically, wastewater (WW) with average production of 2735 $m^3\ y^{-1}$; cow manure (CM) with an estimated total production of 233 t DM y^{-1}; banana and rice plantations with 6 and 175 t DM y^{-1} of biomass, respectively. For experimentation purposes, banana and rice residual biomasses were divided in three (banana lower (BS-Lo), middle (BS-Mid) and upper (BS-Up) parts) and two (rice husk (RHu) and straw (RSt)) distinct fractions, respectively. The total solids (TS) or dry matter (DM) and volatile solids (VS) content of the organic agricultural by-products used in this work are presented in Table 2. Samples of each substrate were collected from the site, taken to the laboratory in Denmark, where the large plant parts were cut down with a pair of scissors to small pieces (5–10 mm) and stored to −18 °C until used.

2.3. Experimental setup of BMP assays I and II

Both biomethanation potential experiments for mono-substrates (BMP assay-I) and co-substrates (BMP assay-II) were performed according to the method described by Angelidaki et al. (2009). BMP assay-I performed in glass shield vessels with 100 and 320 mL of working and total volume, respectively. Three concentrations of the mono-substrates were tested (2, 4 and 8 g VS L^{-1}) to avoid potential overload or inhibition of the used inoculum with the exception of WW where only 10.2 g VS L^{-1} was tested. After the introduction of the substrates, 80 mL of inoculum and deionized water (when needed) were added to obtain the 220 mL headspace in the batch reactors. BMP assay-II performed in glass shield vessels with 118 and 40 mL of working and total volume, respectively. The working volume of its batch reactor was consisted of 32 mL of inoculum and 8 mL of co-substrates and water (if needed). Two different co-digestion combinations (6M and 12M substrate utilization scenarios, respectively) were tested in Batch assay-II, to determine the best co-substrate. Specifically, the concentrations of each substrate in these combinations were based on the reported generation of biomasses in the study site, distributed in 12 (12M)