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# Cost effective dry anaerobic digestion in textile bioreactors: Experimental and economic evaluation

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ABSTRACT

The aim of this work was to study dry anaerobic digestion (dry-AD) of manure bedded with straw using textile-based bioreactor in repeated batches. The 90-L reactor filled with the feedstocks (22–30% total solid) and inoculum without any further treatment, while the biogas produced were collected and analyzed. The digestate residue was also analyzed to check its suitability as bio-fertilizer. Methane yield after acclimatization increased from 183 to 290 Nml$CH_4$/gVS, degradation time decreased from 136 to 92 days and the digestate composition point to suitable bio-fertilizer. The results then used to carry out economical evaluation, which shows dry-AD in textile bioreactors is a profitable method of handling the waste with maximum payback period of 5 years, net present value from $7,000 to $9,800,000 (small to large bioreactors) with internal rate of return from 56.6 to 19.3%.

## 1. Introduction

Solid wastes from agricultural, municipal and industrial activities are major sources of environmental pollution. Large volumes of these wastes are being generated and are increasing immensely due to population growth and high consumption rate. Currently, people generate globally about 17 billion tonnes of total solid wastes annually (Chattopadhyay et al., 2009) and it is estimated to reach 27 billion tonnes in 2050 (Karak et al., 2012). These wastes streams usually have a solid content between 15% and 50%. Landfilling is a major practice of disposing solid wastes resulting in emissions of methane and nitrous oxides which contribute to greenhouse effect. Composting and incineration are also common methods of treating these wastes; composting results in emissions of volatile compounds (ketones, aldehydes, ammonia and methane) (Mata-Alvarez et al., 2000) while incineration can lead to significant release of dioxin to the environment (Strange, 2002) if the exhaust gas is not treated properly. There are regulations and standards for management of these wastes, but in addition to this it is essential that other waste management options which are both environmentally friendly and economical are explored. Biogas production through anaerobic digestion is an interesting waste management option for handling the organic fraction of solid waste, as biogas production usually leads to reduced pollution and increased energy production. Studies have shown that anaerobic digestion of these wastes is sustainable and has a great advantage over aerobic treatment because of its improved energy balance (Mata-Alvarez et al., 2000). In addition to biogas production, digestate residue from anaerobic digestion usually contains high content of phosphate and nitrogen, especially in the form of ammonium which is available for plants; it also contains other macro-nutrients and trace elements essential for plant growth (Makádi et al., 2012).

Anaerobic digestion of organic wastes is carried out generally through wet (feedstock with solid concentration between 0.5% and 15%) (Li et al., 2011) and dry (feedstock with solid concentration greater than 20%) (Bolzonella et al., 2003) anaerobic digestion processes. When treating solid wastes in wet anaerobic digestion processes, fresh and recycled water must be added while large reactor volume, high energy for heating and costly dewatering process of the digestate is required. Therefore, processing of solid wastes for biogas production through dry-AD is a better option since they usually have low moisture content. However, for enhanced performance of dry-AD process, a suitable reactor is required; considering the substrate composition, amount of substrate to be treated, and process economy of the reactor (Patinvoh et al., 2017). It also requires an appropriate technology for operation. In this vein, several continuous and batch reactors for dry-AD processes have been employed such as plug flow reactors (Deng et al., 2016; Patinvoh et al., 2017) for continuous dry-AD processes, and completely mixed reactor (Guendouz et al., 2010) for batch dry-AD processes. However, some of these reactors required expert design and constructions, constant monitoring, high capital and operational cost.

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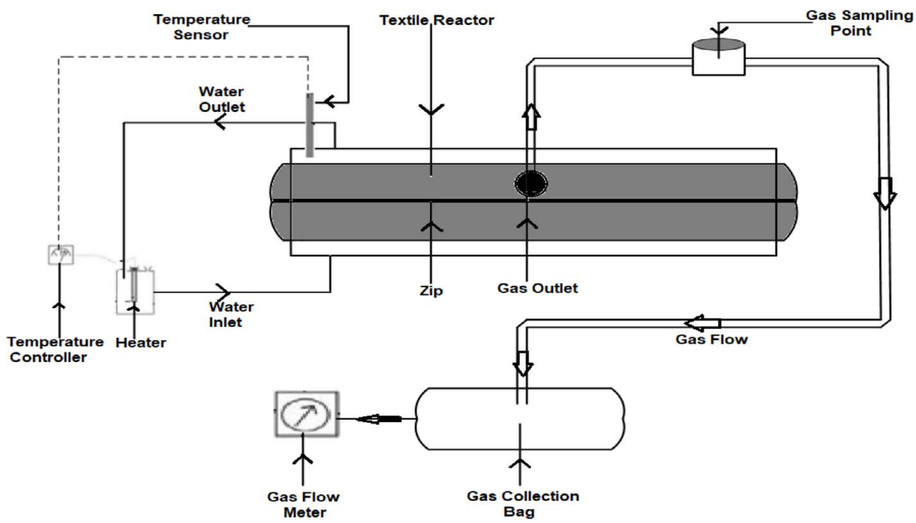


**Fig. 1.** Schematic sketch of the experimental set up.

The most commonly used reactors in developing countries are fixed-dome reactors, floating-drum reactors and polyethylene tubular reactors (usually modelled as plug flow reactors) (Rowse, 2011). The cost of a fixed-dome reactor is relatively low and the reactor is usually constructed underground which makes it less sensitive to seasonal temperature changes but this reactor requires high technical skill for construction (Kossmann et al., 1999). It is also prone to leakages (Kossmann et al., 1999; Rajendran et al., 2013) (porosity and cracks) and utilization of gas produced is less effective as the gas pressure fluctuates substantially. Floating-drum reactor is easy to operate, it provides gas at constant pressure but the steel drum is relatively expensive and requires rigorous maintenance (Kossmann et al., 1999). It requires constant removal of rust and regular painting to avoid gas leakage, this reactor is not also suitable for fibrous substrates because the gas-holder can get stuck in the resulting floating scum (Kossmann et al., 1999). Hence, there is a need for reactors that are robust in nature, easy to maintain, suitable for dry digestion processes and cost effective. An innovative textile-based bioreactor which is durable, cost effective and easy-to-operate was developed for biogas production, and it was found to be effective and economical for wet anaerobic digestion of organic fraction of municipal solid wastes (Rajendran et al., 2013).

In this work, the potential of dry anaerobic digestion in the textile-based bioreactor was studied in batch process, and its technical and economic aspects were evaluated. Manure bedded with straw was used as an example of the substrate abundantly available at farms. Repeated batch digestion processes were investigated, the TS in the reactor was gradually increased in order to acclimatize the inoculum to the substrates under solid state condition and thereafter increase the amount of wastes treated. The residue after biogas production was analysed to check its suitability as bio-fertilizer. Additionally, the economic analysis was carried out to evaluate this technology.

## 2. Materials and methods

### 2.1. Bioreactor

A new design of innovative textile reactor at laboratory scale was developed and supplied by FOV Fabrics AB (Borås, Sweden). It was made of advanced textiles and sophisticated coated polymers which makes the bioreactor durable, resistant to digesting bacteria and chemicals, easily transportable and highly resistant to UV light and high temperature (up to 80 °C) (Rajendran et al., 2013). The reactor is made of high quality polyester PVC coated fabrics; it is a horizontal bioreactor of 184 cm length, 54 cm breadth and had a total volume of about 90 L. The bioreactor was maintained at 25 °C by circulating water through water jacket. This bioreactor had an air tight zip which was opened for feeding and closed after feeding; it also had an opener for gas outlet. The reactor was examined for leakages by filling with water and air before starting the experiment. Fig. 1 shows the schematic sketch of the experimental set up together with other accessories, such as gas collection bag, sampling point for biogas compositional analysis and the gas flow meter (Drum-type gas meter, TG 05 Model 5, Ritter, Germany) for measuring the produced biogas volume.

### 2.2. Substrate and inoculum preparation

Cattle manure bedded with straw and untreated wheat straw was obtained from a farm outside Borås (Rådde Gård, Sweden). During the experimental period, two different batches of the substrates were obtained; the amount of straw in manure was higher in the second batch collected compared to the first batch. The first batch was used for first experiment while second batch was used for the second and third experiments. The manure was shredded manually to reduce the particle size of straw in the manure. The untreated wheat straw was milled to particle size of 0.5–2 mm, after which the feedstocks were characterized.

Inoculum was obtained from a digester treating wastewater sludge and operating at mesophilic conditions (Vatten and Miljö i Väst AB, Varberg, Sweden). The inoculum was filtered through a 2-mm porosity sieve to remove sand, plastic and other unwanted particles after which it was acclimatized for five days prior to use. The inoculum was centrifuged at $7{,}600 \times g$ using continuous centrifuge to obtain a TS content of 7.0 ± 0.24%. The inoculum from wet fermentation with TS content of 3.53 ± 0.01% was centrifuged in order to reduce its water content since the textile reactor is studied under dry anaerobic digestion. The inoculum after centrifuge having TS and VS content of 7% and 4% respectively was then used for the first batch experiment.

### 2.3. Experimental procedure

Manure bedded with straw was mixed with required amount of untreated wheat straw to increase the C/N ratio; the C/N ratio was kept between 20:1 and 25:1 throughout the experiment. The amount of untreated straw needed to increase the C/N was calculated according to Eq. (1) (AAFRD, 2005) and the required amount added is shown in Table 3. During the first digestion process (unacclimatized inoculum), the total feedstock with 22% TS was inoculated with the initial inoculum (7%TS and 4%VS) keeping a volatile solids (VS) ratio ($VS_{inoculum}$ to $VS_{substrate}$) at 1:1 thereby having total TS of 10% in the reactor. A nutrient solution with composition according to Angelidaki