Bioresource Technology 233 (2017) 166–175

Contents lists available at ScienceDirect

Bioresource Technology

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

Dry anaerobic digestion of food waste and cardboard at different substrate loads, solid contents and co-digestion proportions

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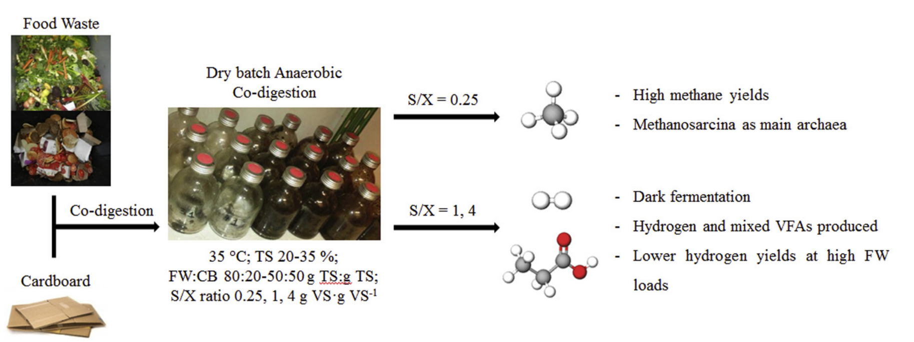
HIGHLIGHTS

- The initial substrate to inoculum ratio is a critical parameter in dry anaerobic co-digestion.
- Methanogenesis was favored at low substrate to inoculum ratios (0.25 g VS·g VS^{-1}).
- *Methanosarcina* as main archaea after digestion.
- Efficient acidogenic fermentation occurred at higher substrate to inoculum ratios.
- Lower hydrogen yields at higher food waste loads.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 January 2017
Received in revised form 24 February 2017
Accepted 25 February 2017
Available online 28 February 2017

Keywords:
Biomethane
Biohydrogen
Dark fermentation
High-solids
Platform molecules

ABSTRACT

The increasing food waste production calls for developing efficient technologies for its treatment. Anaerobic processes provide an effective waste valorization. The influence of the initial substrate load on the performance of batch dry anaerobic co-digestion reactors treating food waste and cardboard was investigated. The load was varied by modifying the substrate to inoculum ratio (S/X), the total solids content and the co-digestion proportions. The results showed that the S/X was a crucial parameter. Within the tested values (0.25, 1 and 4 g VS·g VS^{-1}), only the reactors working at 0.25 produced methane. *Methanosarcina* was the main archaea, indicating its importance for efficient methanogenesis. Acidogenic fermentation was predominant at higher S/X, producing hydrogen and other metabolites. Higher substrate conversions (≤48%) and hydrogen yields (≤62 mL·g VS^{-1}) were achieved at low loads. This study suggests that different value-added compounds can be produced in dry conditions, with the initial substrate load as easy-to-control operational parameter.

1. Introduction

The production of food waste (FW), which can be defined as the mass of food lost or wasted during the part of the food supply chains leading to edible products for human consumption, is a global problem (Gustavsson et al., 2011). Currently, about 1.3 billion tons of food (one third of the production for human consumption) is wasted every year (FAO, 2012). Moreover, this number is expected to increase in the coming years due to economic and population growth, particularly in developing countries. On a global scale, the production of urban FW is expected to increase by 44% from 2005 to 2025 (Melikoglu et al., 2013). In Europe, this raise

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http://dx.doi.org/10.1016/j.biortech.2017.02.126
0960-8524/

is expected to be from 89 million tons in 2006 to 126 million tons in 2020 (Monier et al., 2010).

Nowadays, most of the FW is disposed in landfills or incinerated, practices associated with different issues, such as rising costs of waste disposal, lack of space, leaching, public environmental concern and emission of toxic and greenhouse effect gases (Curry and Pillay, 2012; Uçkun Kiran and Liu, 2015). Therefore, it is necessary to develop and optimize technologies that allow a proper treatment of this biowaste. Anaerobic processes stand as a well-established technology that permits an effective and environmental-friendly treatment of waste and its valorization in the form of several products, such as biomethane, biohydrogen, alcohols or volatile fatty acids (VFAs) (Banks et al., 2012; Kim et al., 2014; Wang et al., 2015). Particularly, anaerobic digestion (AD) in dry conditions (>20% total solids; TS) is a promising alternative, due to several advantages when compared to wet digestion, *e.g.* lower water requirement and/or smaller reactor volume (Karthikeyan and Visvanathan, 2013).

However, AD of FW is a complex process, associated in many cases with the accumulation of ammonia and VFAs, leading to inefficient performances and even to process failure (Agyeman and Tao, 2014; Dai et al., 2013; El-Mashad and Zhang, 2010; Owamah and Izinyon, 2015; Wan et al., 2013; Wang et al., 2014; Zhang et al., 2012a,b). Co-digestion, *i.e.* simultaneous treatment of two or more substrates, has been proved to be an economically feasible option to overcome these complications (Dai et al., 2016; Lin et al., 2011). Co-digestion may favor the methanogenic/acidogenic processes by balancing the nutrient and carbon contents, diluting inhibitory compounds, adjusting the moisture content or increasing the buffering capacity of the system (Mata-Alvarez et al., 2011). Particularly for FW dry AD, a suitable co-substrate should have a high C/N ratio, a high TS content and provide enough buffering capacity to avoid sudden pH drops. Paper/cardboard waste (CB) fulfills all these requirements, with negligible N contents, having high buffering capacities and TS contents and being slowly biodegradable. In addition, CB is a particularly convenient co-substrate for centralized co-digestion with commercial FW in urban areas, where FW and CB are usually the main organic solid waste streams (Kim and Oh, 2011; Zhang et al., 2012a,b). To give an idea of the importance of CB waste streams, in a study dealing with the composition of municipal solid waste in different countries in the 90s, paper and cardboard waste represented up to 36.8% of the total municipal waste (Hogg et al., 2002).

Besides the great potential of this option, few studies have been carried out to assess the feasibility of FW and CB dry co-digestion. Zhang et al., 2012a,b co-digested FW and CB in wet AD at a ratio 53:47 $g\ VS \cdot g\ VS^{-1}$, achieving effective methane production at a load of 3 $g\ VS \cdot L^{-1} \cdot d^{-1}$ and proving that CB addition led to less accumulation of ammonia and VFAs. In a recent study, Asato et al. (2016) co-digested FW and CB (wet AD) at different COD loads and co-digestion proportions. They concluded that concentrations of FW $\geq$ 18.75 $g\ COD \cdot L^{-1}$ caused inhibition, while mixtures with $\geq$75% of CB avoided failure of methanogenesis. In dry conditions, Kim and Oh (2011) achieved a stable methane production (up to 260 ml $CH_4 \cdot g\ COD^{-1} \cdot d^{-1}$) without significant VFA accumulation at OLRs up to 10 $g\ TS \cdot L^{-1} \cdot d^{-1}$ and with a co-digestion ratio FW:paper of 7:1 $g\ TS \cdot g\ TS^{-1}$. To our knowledge, no other study has been performed dealing with FW and CB co-digestion at high TS contents. In addition, no study has been performed to optimize critical variables for dry co-digestion of FW and CB, such as the substrate load, the co-digestion ratio or the TS contents. Moreover, taking into account the huge variability of the FW characteristics worldwide, producing comparable experiments (always supplying extensive characterizations of the substrates and the inoculum) is much more important than when using more simple/homogeneous substrates.

Accordingly, the aim of this study was to evaluate the feasibility of FW valorization by dry anaerobic co-digestion with CB using batch systems, which allowed testing different conditions simultaneously. More precisely, the influence of the initial FW load (varied by modifying the substrate to inoculum ratio (S/X), the TS content and the FW:CB proportions) on the performance of a dry batch anaerobic co-digestion system using CB as sole stabilization agent, was investigated for the first time. In addition, the physicochemical characteristics of the substrates and the microbial communities in the reactors were studied extensively.

2. Materials and methods

2.1. Substrate and microbial inoculum

A model FW was prepared according to the VALORGAS report (VALORGAS, 2010) and used as substrate (Table 1). The FW mixture was finely milled and blended to ensure its homogeneity. Compact cardboard (branded "Cartonnages Michel") with a density of 1.42 $kg \cdot m^{-3}$ was shredded to less than 1 mm and used as co-substrate.

The microbial inoculum consisted on a mixture of (i) a centrifuged granular sludge issued from a mesophilic industrial UASB reactor treating sugar factory effluents and (ii) a dried digestate originated from a thermophilic industrial plant treating the organic fraction of municipal solid waste used only to increase the TS content. This latter digestate was dried at 105 °C for at least 24 h and the resulting material was finely milled and sieved at 1 cm. Both fractions were mixed in a proportion 1:2 (wet weight basis), to obtain a final TS content of 74.19% (59.06% VS/TS; VS standing for volatile solids). This high TS proportion of the inoculum allowed starting the reactors with TS contents up to 35%. Although this process resulted in a very particular inoculum, this was the only possible way to achieve the desired TS contents in the reactors. This allowed elucidating clearly the influence of this parameter on the AD process. In addition, the dried digestate added was the source of solids closest to those that can be found in a regular high-solid digestate.

2.2. Dry batch anaerobic co-digestion

The batch assays were carried out in flasks with a total volume of 600 mL. The initial FW concentrations in the reactors were adjusted by modifying the initial TS content (20, 27.5 and 35%), the S/X (0.25, 1 and 4 $g\ VS \cdot g\ VS^{-1}$) and the FW:CB co-digestion ratio (80:20, 65:35 and 50:50 $g\ TS \cdot g\ TS^{-1}$). Thirteen different combinations of these independent variables were defined following an optimal statistical design and varying the initial FW load from 26.4 to 252 $g\ VS \cdot L^{-1}$ (Table 2). After addition of all the components needed (*i.e.*, FW, CB, inoculum and tap water), the flasks were sealed and the volume of the headspace was accurately determined by measuring the pressure in the vessel before and after

Table 1
Components of the model food waste.

Component	Ingredient	Proportion (% in wet basis)
Fruits and vegetables	Apples	25.9
	Lettuce	25.9
	Potato	25.9
Pasta/rice/flour/cereals	Couscous	4.80
Bread and bakery	Bread	6.20
Meat and fish	Chicken	4.10
	Beef	4.10
Dairy products	Cheese	1.90
Confectionery/snacks	Biscuits	1.50