Renewable and Sustainable Energy Reviews 93 (2018) 380–399

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW): Progress and challenges

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ARTICLE INFO

Keywords:
Anaerobic
Co-digestion
OFMSW
Sewage Sludge
Biogas
Methane
Hydrogen

ABSTRACT

Anaerobic digestion (AD) of the organic fraction of municipal solid waste (OFMSW) offers the possibility of a clean and renewable energy source – i.e. biogas. However, OFMSW lacks certain characteristics that may limit its efficacy as such a resource. Bio-resources such as sewage sludge and animal wastes have these characteristics and so may be used to enhance OFMSW's digestion. Anaerobic co-digestion (AcoD) of OFMSW with sewage sludge has been extensively studied and applied successfully at full-scale. Pre-treatments can increase substrate biodegradability and so biogas yield, but these may need further investigation to determine economic viability. Mathematical modeling has been shown useful in aiding selection of appropriate combinations of substrates and pretreatment for co-digestion (e.g. substrate type and mix ratio). This review also considers the fate of the digestate following such anaerobic co-digestion. The difficulties in implementation of the co-digestion approach need not necessarily be technical in nature but can be due to management issues.

1. Municipal solid waste: management and bottlenecks

Management of municipal solid waste (MSW) has become a major global concern due to increasing urbanization, consequent generation of such waste, and the adverse impacts on public health and the environment. Current global MSW generation levels stand at approximately 1.3 billion tonnes per year (1.2 kg per capita per day) and is expected to increase to about 2.2 billion tonnes per year by 2025. The OECD countries generate approximately 572 million tonnes of MSW per year (avg. 2.2 kg/capita.day) while Sub-Saharan Africa produces approximately 62 million tonnes per year of MSW (avg. 0.65 kg/capita.day). East Asia and the Pacific Region produce approximately 270 million tonnes per year (avg. 0.95 kg/capita.day), and China contributes 70% of this regional total. In Eastern and Central Asia, the MSW generation is around 93 million tonne per year (avg. 1.1 kg/capita.day) while South Asia produces 70 million tonnes (avg. 0.45 kg/capita.day). The yearly MSW generation in the Middle East and North Africa, and Latin America and the Caribbean are 160 million tonnes (avg. 1.1 kg/capita.day) and 63 million tonnes (avg. 1.1 kg/capita.day), respectively [1].

MSW disposal is typically associated with landfilling, thermal treatment (in high income countries), composting, and open dumping

Abbreviations: AAD, acidogenic anaerobic digestion; ABR, anaerobic baffled reactor; AcoD, anaerobic co-digestion; AD, anaerobic digestion; BA, bottom ash; BMP, biochemical methane potential; CHP, combined heat and power generation; CM, cow manure; FOG, fats, oils and grease waste; FA, fly ash;; FVW, fruits and vegetable waste; FW, food waste; GHG, greenhouse gases; GSW, gelatin solid waste; GWP, global warming potential; HRT, hydraulic retention time; HS-OFMSW, hydro-mechanically separated organic fraction of municipal solid waste; IS, industrial sludge; LCA, life cycle assessment; LCFA, long chain fatty acids; MS-OFMSW, mechanically separated organic fraction of municipal solid waste; MSW, municipal solid waste; MSWI, municipal solid waste incinerator; OFMSW, organic fraction of municipal solid waste; OLR, organic loading rate; O and M, operation and maintenance;; PHA, polyhydroxyalkanoates; PM, pig manure; PS, primary sludge; SC-OFMSW, separately collected organic fraction of municipal solid waste; SHW, slaughterhouse waste; SMP, specific methane production; SRT, sludge retention time; SS, sewage sludge; sOFMSW, simulated organic fraction of municipal solid waste; SS-OFMSW, source-sorted organic fraction of municipal solid waste; SSTR, semi-continuous stirred tank reactor; TS, total solids; VFA, volatile fatty acids; VOC, volatile organic compounds; TVS, total volatile solids; VSS, volatile suspended solids; WAS, waste activated sludge; WWTP, wastewater treatment plants

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https://doi.org/10.1016/j.rser.2018.05.051
Received 29 June 2017; Received in revised form 20 April 2018; Accepted 21 May 2018

(in low- and lower-middle income countries). Landfilling of MSW, if inappropriately performed, may contaminate nearby water-sources and soil with leachate carrying heavy metals, persistent organic pollutants and microbial pathogens. Poorly operated landfills also cause air pollution from emission of odors, greenhouse gases (GHG), and volatile organic compounds (VOCs). The solid waste management sector is responsible for almost 5% (1460 mt CO_2e) of the total global GHG emissions and 9% of the methane released. It can also threaten public health by attracting disease vectors and exposing people living near waste disposal sites to harmful components therein. Transportation of MSW to disposal sites contributes to CO_2, SO_2, NOx, odor and other atmospheric pollutants [1–3] from the energy required and emissions during the transfer. Incineration has high capital and operating costs, generates ash, and may emit particulate and gaseous pollutants (heavy metals, CO_2, N_2O, dioxins and furans, and persistent organic pollutants) to the atmosphere if there is inadequate air pollution control. Advanced thermal treatment i.e. pyrolysis and gasification are technically challenging, relatively unproven at commercial scale, and may not be energy positive since the generated energy may be needed to power the process. Open-burning of waste causes severe air pollution due to the low- temperature combustion [4]. Composting is facing a lack of public interest mainly due to the low value of the product (i.e. the compost) and limited waste volume reduction.

As a result of public health and environmental protection issues, apprehensions over land use and loss of resources, climate change concerns, and stringent organic waste disposal regulations, efforts are increasingly made towards increasing reduction, recycling and recovery of useful materials from waste. A key component, which is technically and economically feasible for recovery, is energy from the organic fraction of municipal solid waste (OFMSW) (also known as bio-waste). MSW typically comprises 46% organic fraction (food scraps, yard waste, wood, process residues) followed by 17% paper, 10% plastics, 5% glass, 4% metal and 18% others. The organic fraction comprises a greater proportion in MSW arising from low and middle-income communities (50–70% of total MSW) than from high-income communities (20–40%) [1]. If it is managed efficiently, OFMSW can be a valuable source of renewable energy.

Among the several technical options available for energy recovery from MSW, anaerobic digestion (AD) is potentially a suitable route for such energy recovery from OFMSW (Fig. 1).

AD turns organic matter into two valuable products: (a) energy-rich biogas, a renewable fuel which can be used to generate electricity, heat, or as a substitute for natural gas and transportation fuel, and (b) nutrient rich digestate, which can be utilized directly or composted before use in landscaping or agriculture. AD for OFMSW treatment is a mature technology with over 560 CE plants for power generation reported worldwide. These have combined capacity of more than 7.3 TWh per year [5]. OFMSW is highly biodegradable with relatively low inert material and micro-contaminants, and typically has a high-energy yield of upto 200 m^3 of biogas (≈ 400 kWh of power) per tonne of OFMSW treated [6] or a methane yield of up to 330 L/kg total volatile solids (TVS) [7]. There is possibility for a 1 million people equivalent facility to recover up to 200 MWh per day of electric energy, 420 MWh/ day of heat, and 390 t/day of compost. Use of energy derived from biogas instead of fossil fuels would help reduce CO_2 emissions at 200–300 kg CO_2/t of biowaste. The use of digestate in place of mineral fertilizers provides a further reduction in CO_2 emissions by 30–40 kg CO_2/t of biowaste [8].

2. OFMSW characterization

OFMSW can comprise food waste (FW), yard waste, paper, newspaper and other organic wastes, although each of these organic fractions have different C: N ratios eg. < 20 for food and yard waste and > 100 for mixed paper [9]. C: N ratios in the range of 25–30 have been considered optimum for AD of OFMSW [10]. If harvesting methane is an objective, then biogas production does depend on the nature of the organics in the feedstock, pH, temperature, moisture content, and the feedstock's carbon-to-nitrogen ratio. Table 1 summarizes typical characteristics and methane yield for three kinds of OFMSW, namely: mechanically separated OFMSW (MS-OFMSW), source sorted OFMSW (SS-OFMSW), and separately collected OFMSW (SC-OFMSW).

Characterization of OFMSW properties need to be cognizant with the regional, seasonal and socio-economic contexts. The physical, chemical, elemental and bromatological characteristics of OFMSW from 43 cities in 22 countries have been compiled by Campuzano and González-Martínez [11] (Table 2). The variation in waste characteristics was ascribed to the different cultural lifestyles and waste management systems found among these countries. Such variation does not, therefore, allow a generalization of the waste characteristics. Site-specific analysis do provide a better understanding of the characteristics of a particular waste and this would be necessary for activities such as better biogas recovery.

3. Anaerobic digestion (AD) of OFMSW

AD has often been used for sewage sludge (SS) and livestock wastes treatment. In 2013, the majority of AD plants in Europe (13,800) and the USA (2200) were applied on these two types of wastes. AD is also widely applied in China (40 million plants), India (5 million plants) and Nepal (300,000 plants). These numbers would, however, include applications at the small unit and community levels [4]. The application of AD on organic wastes has increased in appeal from a policy-making standpoint as it is now considered a reliable technology [8]. However, the application of AD to OFMSW is still relatively limited. The latter has been due to issues encountered such as high solids content, large particle size, slowly biodegradable components (lignin-rich, woody wastes), and the waste's heterogeneous nature, which makes process control challenging [7]. Furthermore, contaminated feedstock has been known to halt the AD process as well as make the digestate unfit for land application either directly or as compost [4].

It is no surprise then earlier studies had reported poor biogas yields (60 m^3/t) and various mechanical problems with the anaerobic reactors deployed. Cecchi et al. [8] summarized several experiences with failure of full-scale dry reactors (≈35%TS) treating MS-OFMSW in Switzerland [12], Verona and Bassano in Italy [13], and Barcelona and other Spanish locations [14]. Accumulation of toxic compounds, mass transfer rate limitations of substrate to microbes and biomass concentration were considered potential difficulties. OFMSW is typically characterized by high total solids (TS) concentration (30–50%), high C/N ratio, macro and micro-nutrients deficiency (nitrogen and trace metals), and presence of toxic compounds (heavy metals and phthalates) Such characteristics can limit successful digestion [7]. These difficulties have led to interest in the use of co-substrates in OFMSW digestion – i.e. co-digestion. Anaerobic co-digestion (AcoD) of OFMSW with various co-substrates has shown potential for increased biogas production while offering combined and more stable treatment of two or more problematic wastes for resource-constrained communities [15].

4. Anaerobic co-digestion (AcoD)

AcoD emerged in the late 1970s, allowing treatment of a wider range of organic wastes. AcoD of two or more substrates provide better availability and balance of macro- and micro-nutrients (for good microbial growth), dilution of toxic or inhibitory compounds, moisture balance, and better buffering capacity to the mixture. AcoD allowed for positive synergistic effects on process efficiency, increase in the biodegradable component, broadening the microbial community involved in the digestion process, and higher active biomass concentrations. These led to improved process stability and higher biogas generation [16,17] (Fig. 2). The economic benefits, which can be derived, can