Progress in Energy and Combustion Science 51 (2015) 49–66

Contents lists available at ScienceDirect

Progress in Energy and Combustion Science

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

Mathematical modeling of solid-state anaerobic digestion

Fuqing Xu [a], Yebo Li [a,*], Zhi-Wu Wang [b,**]

[a] Department of Food, Agricultural and Biological Engineering, The Ohio State University/Ohio Agricultural Research and Development Center, 1680 Madison Ave., Wooster, OH 44691, USA
[b] Department of Civil and Environmental Engineering, Virginia Tech/Occoquan Laboratory, 9408 Prince William Street, Manassas, VA 20110, USA

A R T I C L E I N F O

Article history:
Received 17 July 2015
Accepted 5 September 2015
Available online 23 October 2015

Keywords:
Kinetics
ADM1
SS-AD
Bioenergy
Methane
Biogas

A B S T R A C T

Solid-state anaerobic digestion (SS-AD) technology for the conversion of solid organic wastes to renewable energy has been widely studied and applied during the past decades. Due to the nature of the solid medium, the SS-AD process is significantly different from the traditional liquid anaerobic digestion in many aspects, such as the distribution of microbes and substrates in the reactors, mass transfer, and reaction kinetics. Extensive efforts have been dedicated to developing mathematical models for understanding SS-AD mechanisms, predicting its performance, and improving process control. In this review, SS-AD mathematical models derived from theoretical, empirical, and statistical approaches are critically reviewed and discussed regarding their different assumptions, structures, applications, and limitations. Based on this review, it was concluded that significant efforts should be devoted to experimental verification of the model assumptions, measurement of important kinetic parameters specific for SS-AD, and generation of sufficient data for model validation. It is necessary to synergistically improve modeling and experimental approaches in order to gain deeper insight into the SS-AD mechanism. Several promising research directions for the future development of experimental and modeling approaches in SS-AD are proposed.

Contents

Abbreviations: 1D, one-dimensional; 3D, three-dimensional; AD, anaerobic digestion; ADM1, Anaerobic Digestion Model No. 1; ANN, artificial neural network; CFD, computational fluid dynamics; COD, chemical oxygen demand; DOC, dissolved organic carbon; FISH, fluorescence in situ hybridization; L-AD, liquid anaerobic digestion; LCFAs, long chain fatty acids; MLR, multiple linear regression; NIR, near infrared spectroscopy; OFMSW, organic fraction of municipal solid waste; SS-AD, solid-state anaerobic digestion; SSTR, semi-continuous stirred tank reactor; TS, total solids; VFAs, volatile fatty acids.

* Corresponding author. Department of Food, Agricultural and Biological Engineering, The Ohio State University/Ohio Agricultural Research and Development Center, 1680 Madison Ave., Wooster, OH 44691, USA. Tel.: +1 330 263 3855; Fax:+1 330 263 3670.
E-mail address: li.851@osu.edu (Y. Li).
** Corresponding author. Department of Civil and Environmental Engineering, Virginia Tech/Occoquan Laboratory, 9408 Prince William Street, Manassas, VA 20110, USA. Tel.: +1 703 361 5606 ext. 119; Fax: +1 703 361 7793.
E-mail address: wzw@vt.edu (Z.-W. Wang).

http://dx.doi.org/10.1016/j.pecs.2015.09.001
0360-1285/

1. Introduction

1.1. Development of solid-state anaerobic digestion (SS-AD) technology

Anaerobic digestion (AD) is a biological process in which organic matter is decomposed by an assortment of microbes in oxygen-free or oxygen-lean conditions to produce biogas (about 40–70% CH_4 and 30–60% CO_2) [1]. Since the 1990s, increased energy prices, concerns of global warming, as well as the decreasing capacity of landfills have stimulated development of AD technology to produce renewable energy from various organic wastes, such as the organic fraction of municipal solid waste (OFMSW), sewage sludge, agricultural residues, and energy crops [2–5]. Among these, solid organic waste and lignocellulosic biomass were considered to be the major source of feedstock for renewable energy production [6–8]. For example in Germany, the global leader of AD technology, solid organic material contributed two-thirds of the total biogas potential (Fig. 1) [3]. As of 2012, there were 9766 agricultural-based biogas plants in Europe, with 7515 in Germany, and these biogas plants mainly used maize silage, sugar beet, lawn grass, crop residues, and dedicated energy crops as feedstocks [3,9].

Based on the operating total solids (TS) content, AD can be categorized as liquid-AD (L-AD) systems, which operate at TS content of less than 15%, and solid-state AD (SS-AD) systems that operate at TS content higher than 15% [10]. L-AD has been widely applied to treat liquid organic waste, such as sewage sludge, animal manure, and food processing wastewater [11,12]; while SS-AD is suitable to handle solid organic materials, such as yard waste, crop residues, and OFMSW [10,13]. The availabilities and methane yields for these various substrates have been extensively reviewed [13–15]. Compared with L-AD, SS-AD has the advantages of high solid loading capacity, increased volumetric biogas productivity, and reduced energy needs as there is less water to heat [16]. Moreover, SS-AD is free of stratification problems incurred by floating of fibrous material, and also tolerates inerts, such as sand and stones [17]. Due to these reasons, SS-AD has captured a higher market share of the total installed AD capacity in Europe during the past 20 years, and its dominance has further increased since 2008 (Fig. 2) [18,19].

Various SS-AD technologies have been developed during the past 20 years. Some have been successfully commercialized, while most of them are still being evaluated at lab or bench scales [13]. These digesters can be categorized based on the design (vertical, horizontal, inclined), feedstock (single, co-digestion), configurations (one-, two-, multi-stages), modes of operation (batch, continuous, semi-continuous), or operating temperature (psychrophilic, mesophilic, and thermophilic). Biogas injection, internal mechanical agitation, and pre-mixing/leachate recirculation are three commonly adopted methods for mixing. Currently, the majority of SS-AD digesters in Europe operate in the one-stage mode feeding a single feedstock at mesophilic temperatures [13,18,19]. Several predominant commercial SS-AD systems are listed in Fig. 3. More details for these technologies, such as installation location and capacity, operating temperature, and retention time, have been reviewed in previous publications [13,20].

1.2. SS-AD modeling efforts

Although believed to be a promising technology with multiple economic and environmental benefits, a major disadvantage of SS-AD compared to L-AD is the relatively low reaction rate [23,24]. One possible reason is attributed to the slow release of the soluble substrates for microbial metabolism due to the retarded hydrolysis of the solid substrate; the other reason is believed to be the difficulty of providing sufficient agitation and thus compromised mass transfer, which reduces the microbial accessibility to substrates and also the dispersion of inhibitors [25–27]. Thus, more investigation about the mass transfer phenomena in the solid, liquid, and gas phases in SS-AD is required to improve the efficiency of the process.

To date, the operations of SS-AD systems are usually performed empirically, and there is still a lack of mechanistic tools for accurate process control [28]. Experimental studies and optimization for SS-AD are time consuming and costly due to the demand for space, equipment, and labor [29,30]. It is commonly agreed that the application of mathematical models can be used to improve the engineering process, explain the mechanisms, understand the effects and interaction of different operating parameters, and predict system performance [31–33]. Hence, more attention is required for the development of adequate mathematical models for SS-AD.

Different SS-AD models have been developed in the past decades to improve the design of the SS-AD processes [31,33,34]; however, there is no review summarizing the mathematical models for SS-AD. Unlike the intensive researches dedicated to L-AD modeling, which have converged into a unified framework, namely the Anaerobic Digestion Model No. 1 (ADM1) [35], current theoretical models proposed for SS-AD are diverse (Fig. 4). The reactor designs, mass transfer, reaction kinetics, and rate limiting steps in SS-AD are essentially different from those of the L-AD process [26,36,37]. Thus, SS-AD modeling needs to take these special features into account (Table 1). This review evaluates the mathematical approaches for each SS-AD model based on the analysis of their assumptions, derivations, capacities, and limitations. An overview of the models to be discussed is summarized in Table 2. Key areas in SS-AD modeling that require further research are also discussed. It is our intention to offer deep insights into the state-of-the-art of the mathematical