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A REVIEW ON THE USE OF COMPUTATIONAL FLUID DYNAMICS AND SONICATION AS A TOOL FOR OPTIMIZING THE ANAEROBIC SEWAGE SLUDGE DIGESTERS

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Abstract

Anaerobic Digestion (AD) is a biological process historically applied to wastewater treatment sludge which reduces Chemical Oxygen Demand (COD) of complex organic substrate and converts it into biogas, which is mainly composed by methane and carbon dioxide. During this process, organic matter is progressively converted into simpler and smaller sized organic compounds forming biogas and digestate as final products. This digestate is rich in nutrients and microelements and it is suitable for utilization in agricultural contexts. At present, there is an emerging need to manage correctly bio-waste from its generation stage to its safe disposal and to reduce its impact on the environment. Sonication is known to facilitate the migration of moisture through natural channels or other channels created by wave propagation. Powerful sonication can significantly change the structures and properties of sludge, disintegrate sludge flocs, enhance solid/liquid separation in cake filtration processes via accelerating the agglomeration process, improve bio-degradability or bioactivity of the treated sludge. The objective of this paper is to review the existing scientific literature pertaining to biomethanation of sewage sludge, effect of sonication and computational fluid dynamics models.

Keywords: Anaerobic digestion (AD); Mathematical model; Biomethanation; Sonication; Total solids; Computational Fluid Dynamics (CFD).

1. Introduction

Energy has a major economical and political role as an important resource traded worldwide. Energy consumption in the developed countries has been more or less stabilized whereas in developing countries like India it is increasing at a high rate. The Government is looking forward to Biomethanation Technology (BT) as a secondary source of energy by utilizing industrial, agricultural and municipal wastes. A large amount of money is being invested in this direction with various projects under implementation and many to follow them. Hence the long-term sustainability of the technology needs to be judged. In this paper the prevailing situation is analyzed in keeping with the prospects and problems associated with BT in India. Fig. 1 presents typical energy recovery potential of different wastes from urban and industrial sectors (Dhussa and Tiwari, 2000). Fig. 2 shows the parameters responsible for technical feasibility of biomethanation plant (Ambulkar and Shekdar, 2004).

For sludge conditioning, various alternatives have been proposed in the literature which includes Fenton's reaction, pH,adjustment, sonication, and freezing-thawing. Among these methods, sonication is very attractive since it is simple, easy to operate, and secondary pollution free. Sonication is known to facilitate the migration of moisture through natural channels or other channels created by wave propagation. Powerful sonication can significantly change the structures and properties of sludge, disintegrate sludge flocs, enhance solid/liquid separation in cake filtration processes via accelerating the agglomeration process, improve bio-degradability or bioactivity of the treated sludge. Many reports showed that proper sonication could reduce the sludge capillary suction time and bound water content by more than 50% .

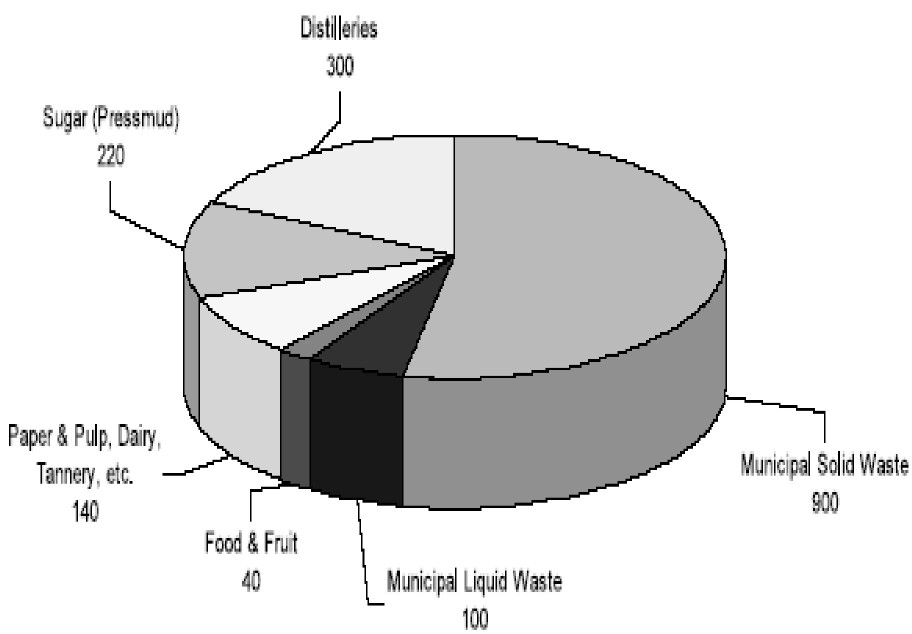

Fig. 1 Energy recovery potential of different wastes from urban and industrial sectors (Dhussa and Tiwari, 2000).

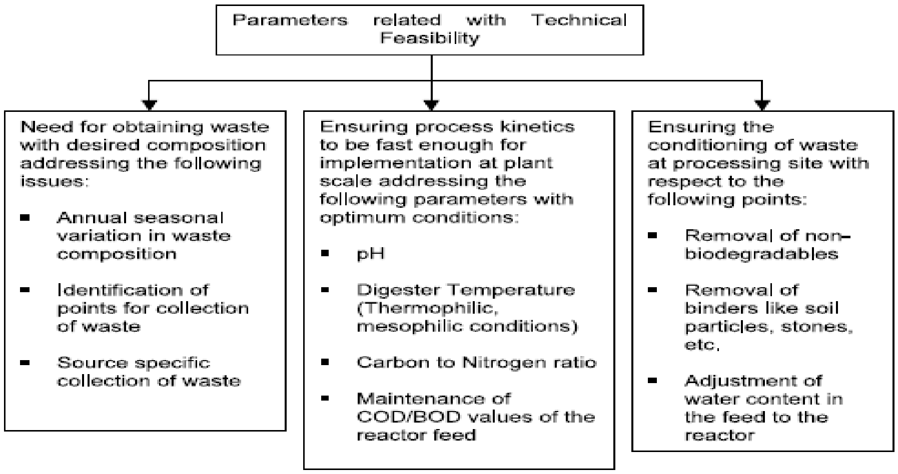

Fig. 2 Parameters responsible for technical feasibility of biomethanation plant. (Ambulkar and Shekdar, 2004).

Anaerobic digestion (AD) has become an increasingly important industrial process. AD is a green technology involving the generation of methane-rich biogas via the biological degradation of regionally available biomass like agricultural and municipal solid wastes and wastewaters. AD processes have for many years been used to treat and sanitize sewage sludge waste from aerobic wastewater and animal manure, reduce its odor and volume, and produce useful biogas. Biogas in turn is a first generation, renewable biofuel that offers the prospect of replacing fossil fuels in the transportation sector and limiting the net greenhouse gas emissions implicated in climate change [Yu et al., 2013]. Based on the solid content of the influent bio-waste, AD can be defined dry, semidry and wet. In dry AD (high-solids digestion), the feedstock to be digested has a Total Solids (TS) content higher than 15%. In semidry AD the solid substrate to be digested has a TS content ranging between 10%-15%. In contrast, wet AD (low-solids digestion) deals with diluted feedstock having a TS content lower than 10% (Li et al. 2011). The economical differences between wet and dry systems are small, both in terms of investment and operational costs. The differences between those systems are more substantial in terms of environmental issues. For instance, while wet systems typically consume one m^3 of fresh water per ton of treated Organic Fraction of Municipal Solid Waste, the water consumption of their dry counterparts is ten-fold less. As a consequence, the volume of wastewater to be discharged is several-fold less for dry systems.

Ideally, process models are supposed to describe the qualitative and quantitative aspects of microbial reactions, ranging from hydrodynamics and mass transfer to population dynamics in different reactor configurations under different environmental and operational conditions. However, the task of obtaining valid required kinetic constants is complicated by the fact that AD is itself a complicated multi-stage dynamic process that entails the concerted effort of several bacterial groups of bacteria. The composition of such groups varies in an unknown manner with changes in retention time, feedstock, temperature, reactor type, and other operating conditions [Yu et al., 2013]. It is known that the rate of hydrolysis and disintegration as a function of different parameters such as pH, temperature, hydrolytic biomass concentration, type of particulate organic matter and particle size.

Even though anaerobic process has significant economic advantage over the aerobic process, it is necessary to understand that anaerobic digestion is an end-of-pipe treatment technology only and is not a profit making venture. Therefore, instead of emphasizing the payback period, industries should invest more for the process automation and control in order to have reliable and consistent performance of the process. In addition, enforcement agencies can also recommend the adaptation of high rate anaerobic digestion technologies. It may also be useful to divert the existing government subsidies given for installation of new anaerobic digestion plants to push the industries for the conversion of their existing aerobic plants to anaerobic process [Kusum Lata et al., 2002].

Mathematical modelling and dynamic simulation have become important tools for design and operation of wastewater and solid waste treatment plants. However, semi-empiric methods and mathematical models based on ideal assumptions are still used for routine reactor design and operation. A design model is a model capable of predicting the reactor volume when the desired treatment efficiency and the operational conditions are set. It is typically based on simplified assumptions aiming at to make the model easy to apply. For instance, steady-state instead of dynamic conditions are assumed.

The objective here is to review the existing scientific literature as it pertains to development of models that involve, among other things, reactor kinetics and mixing, to enhance anaerobic digester design, optimization, scale-up, and operation.

2. Anaerobic Digestion Pathways and Reactions

Overall, the bio-chemical reactions occurring during AD can be classified as heterogeneous reactions (i.e. hydrolysis) and homogeneous reactions (i.e. acidogenesis, acetogenesis and methanogenesis). These very complex reactions transpire via a consortium of microorganisms which includes enzyme-secreting, fermentative, H2-consuming, H2-producing, acetogenic, CO2-reducing, and aceticlastic methanogenic bacteria [Appels et al., 2008; Chynoweth and Issacson, 1987]. These AD reactions result in the formation of intermediates, release, their dissolution into the aqueous phase, and their metabolic conversion into products. Death and lysis of viable bacteria, such as anaerobic decomposition of viable, biological solids (e.g. waste activated sludge, algae), is first needed prior to the uptake of organic compounds. Organic compounds in the sludge (e.g. lipids, proteins, and carbohydrates) are then biologically decomposed by extra-cellular enzymes (e.g. lipase, protease, and cellulase) to small and soluble products that can then be transported across bacterial cell membranes and undergo various intra-cellular metabolic processes. There they are converted to intermediate compounds like fatty acids, amino acids, acetic acids, sugars, and H2, which are ultimately converted to biogas comprised primarily of methane (CH4) and carbon dioxide (CO2) [Bagi et al., 2007].

A comprehensive model detailing the generation and degradation pathways of intermediates with associated interactions was previously developed by Angelidaki et al. [1999]. This simulates co-digestion of complex wastes having different characteristics and compositions via the main pathways depicted (Figure 1). The model features the enzymatic hydrolysis of undissolved carbohydrates and undissolved proteins. It also involves eight types of bacteria. These include (1)

glucose-fermenting acidogens, (2) lipolytic bacteria, (3) LCFAdegrading acetogens, (4) amino acid-degrading acidogens, (5) propionate, (6) butyrate, (7) valerate-degrading acetogens, and (8)

aceticlastic methanogens.

Fig. 3 outlines the important typical pathways for anaerobic degradation of organic matter [Angelidaki et al., 1999].

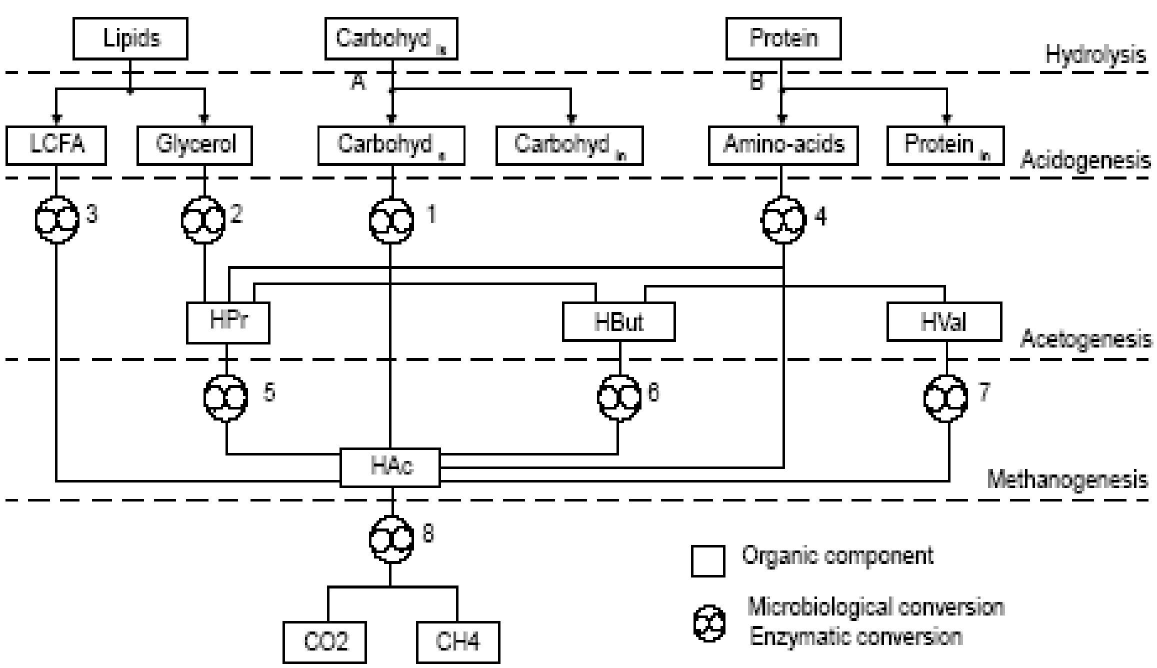

Fig. 3 Important pathways for anaerobic degradation of organic matter (A) hydrolysis of undissolved carbohydrates; (B) hydrolysis of undissolved proteins; (1) glucose fermenting acidogens; (2) lipolytic bacteria; (3) long chain fatty acid (LCFA) degrading acetogens (4) amino acid degrading acidgens (5) propionate (HPr) – degrading acetogens; (6) butyrate (HBut) – degrading acetogens; (7) valerate (HVal) – degrading acetogens; (8) aceticlastic (HAc) – degrading methanogens [Angelidaki et al., 1999]

3. Design Models and Performance-Prediction Models

A design model is a model capable of predicting the reactor volume when the desired treatment efficiency and the operational conditions are set. It is typically based on simplified assumptions aiming to make the model easy to apply. For instance, steady-state instead of dynamic conditions are assumed. Table 1 highlights some performance-prediction models published in the literature (Flavia Liotta, 2013).

Table-1: Performance prediction mathematical models (Flavia Liotta, 2013).

PFR	Activated Sludge	San (1989); San (1992); Lawrence and McCarty (1980); Olsson and Andrews (1978);
	Fluidized Bed	Shieh et al. (1982);
	Biofilter and Trickling Filters	Meunier and Williamson (1981); Baquerizo et al. (2005); Jacob et al. (1996);
TIS/TIS derived	Activated Sludge	Milbury et al. (1965); Braha and Hafner (1985); Muslu (2000a,b).
	Fluidized Bed	Yu et al. (1999)
	Biofilter and Trickling Filters	Fdz-Polanco et al. (1994);
Dispersion	Activated Sludge	Martinov et al. (2010); Mezaoui (1979); Nyadziehe (1980); Sant'Anna (1985); De Clercq et al. (1999); Turian et al. (1975); Lee et al. (1999a,b); Olsson and Andrews (1978); Makinia and Wells (2000);
	Fluidized Bed	El-Temtamy et al. (1979a,b); Muroyama and Fan (1985); Davidson et al. (1985); Lin (1991); Kim and Kang (1997); Michelsen and Østergaard (1970).
	Biofilter and Trickling Filters	Froment and Bischoff 1990; Séguret and Racault (1998); Muslu (1990); Muslu (1984); Muslu and San 1990; Séguret et al.

		(2000)
CFD	Activated Sludge	Le Moullec et al. (2010a,b); Glover (2006)
	Fluidized Bed	
	Biofilter and Trickling Filters	Iliuta and Larachi (2005)

4. **Computational Fluid Dynamics (CFD) Models**

CFD is a techniques applied to solve fluid dynamics models on digital computers. Discretises the reactor using a computational grid and include fundamental mass, momentum and energy conservation equation. It is a powerful tool which allows studying the influences of the operating parameters and the hydrodynamic phenomena at local scale. With a structural approach a CFD model discretises the reactor using a computational grid, formulates and solves the fundamental mass, momentum, and energy conservation equations in space. CFD simulations can define the flow patterns and the retention time distribution to characterize the reactor hydraulic behavior. This information provides a hint to the role of possible hydraulic problems related to the bad plant performance (Flavia Liotta, 2013).

Mixing can promote optimum digester performance by enhancing intimate contact between active microorganisms and feed sludge substrates [Hoffmann et al., 2008]. Computational fluid dynamics (CFD) simulation software allows numerical simulation of mixing effect in a digester [Paul et al., 2004]. CFD can be used also to predict anaerobic digester velocity profiles, rates of energy dissipation, concentrations, and flow streamlines based on specified digester geometry, feed location, physical properties, and operating conditions. In the past decade, CFD has been used to predict digester flow patterns of wastewater treatment units like wastewater ponds, lagoons, and tanks. CFD was first applied to the design of wastewater ponds [Wood et al., 1995; 1998]. The single-phase Euler approach and finite volume numerical method were commonly used. For this, the flow field was calculated in four different ponds types-rectangular facultative, inlet baffle, outlet baffle, and aerates. It was determined later that current designs and operating models pay little attention to the micro-scale effects within the treatment ponds. The effects of inlet formation and basin inlet geometry were additionally simulated, and 2-D CFD models qualitatively demonstrated that the waste pond flow fields were most influenced by inlet geometry. Shilton [2000, 2005] sought to complement and extend on such research of Wood et al. [1998] by presenting the results of a 3-D, turbulent model. CFD has also been applied to the study of lagoons, another common form of simple digester. Baleo et al. [2001] employed two different numerical approaches to obtain lagoon residence time distributions. The first consisted of solving a transport equation for the local fluid mean age via Eulerian reference frame. The second consisted of injecting a virtual particle stream and measuring the time between start injection and end of trajectory via Lagrangian reference frame. Tanks are relatively small compared with ponds and lagoons. Small size of tank digesters permits the use of a more flexible mixing strategy to ensure effective mass and heat transfer. Wu and Chen [2008] accounted for slurry circulation to obtain flow patterns in lab-, pilot-, and commercial-scale digesters and concluded that power input per unit digester volume logarithmically increased for scale-up digesters. Hoffmann et al. [2008] used CFD to model mechanical mixing by an A-310 impeller in a low-solid digester (TS<5%) that was processing

Despite the efforts to apply the concept of non-Newtonian fluid in single-phase models during CFD simulation [Terashima et al., 2009; Wu, 2012], it is important to note that the very complex flow behavior of mixed liquor or waste slurry in digesters also involves segregation and aggregation phenomena [Yu et al., 2013]. These may significantly impact the interactions between active microorganisms and feed sludge, the microorganism retention, and, ultimately, biogas productivity. Therefore, multi-phase non-Newtonian models may be necessary to adequately simulate the complex flow behavior of heterogeous biomass particles in AD sludge, as they differ tremendously from flows of smooth spherical particles in Newtonian fluid. Compared to single-phase Newtonian fluid models, multi-phase non-Newtonian fluid models have not been extensively developed. This has likely held back the understanding, optimization, and commercialization of AD processes [Cui and Grace, 2007]. Despite their added complexity and challenges, development and application of such models represent a significant opportunity to advance the field of anaerobic digestion.

However, despite numerous developments and improvements, this approach still remains difficult to configure the shape of digester for complex and coupled local hydrodynamics, heat and mass transfer and chemical reactions because of the high computational requirements.

5. Summary and Conclusions

This review presents a compilation and discussion of the various models that have been developed to describe Anaerobic Digestion (AD) processes so as to optimize and enhance design and operation of waste treatment plants. The relatively simple and implementable rate-limiting models were first highlighted. However, their diversity and customized development for applications involving specific substrates limited their widespread implementation. It was found that identification of rate-limiting steps at different digester conditions was difficult for AD processes involving complex substrates. It was also found that identification of intermediate fermentation products was very important to assess the capability of digesters.

Because of the complex reaction mechanisms in AD, black box models like artificial neural networks were applied to the simulation of wastewater plants. As these models disregarded reaction mechanisms, they would be more suitable to control, rather than design and scaleup, AD processes. CSTR and PFR models provided the fundamental basis for applying kinetics to design different types of digesters. An axial dispersion model was further developed to account for non-idealities.

Fluid dynamic studies are needed to provide a better understanding of local transport phenomena inside digesters to improve their design and predict their performance. CFD was applied to the simulation of anaerobic digesters to study the effects of mixing. CFD simulation of AD processes can further be augmented with inclusion of comprehensive kinetics [103], although the extremely complex nature of these would likely limit progress in the near-term. It is essential that researchers developing and conducting *in-silico* model simulation communicate effectively with those conducting physical experimentation. Doing so would mutually benefit both groups and help advance the field of mathematical modeling in anaerobic digestion.

Biomethanation technology (BT) may be perceived as a potential alternative as it not only provides renewable source of energy but also utilizes recycling potential of degradable organic portion of solid waste generated by a numerous activities in the country. In India, the Ministry of Non-conventional Energy Sources (MNES) (Government of India) has declared a National Master Plan in 1994, which incorporates BT as one of the major waste-to-energy options to be developed and adopted in the country.

However, despite numerous developments and improvements, this approach still remains difficult to configure the shape of digester for complex and coupled local hydrodynamics, heat and mass transfer and chemical reactions because of the high computational requirements.

Thus, there is a critical need to understand the reactor configuration for optimizing the mixing conditions as a function of operating cost and process efficiency of sewage sludge digester.

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