Solid-State Anaerobic Digestion

Subjects: Engineering, Environmental | Engineering, Chemical | Energy & Fuels
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Anaerobic digestion (AD) is a promising way to produce renewable energy. The solid-state anaerobic digestion (SSAD) with a dry matter content more than 15% in the reactors is seeing its increasing potential in biogas plant deployment. The relevant processes involve multiple of evolving chemical and physical phenomena that are not crucial to conventional liquid-state anaerobic digestion processes (LSAD). A good simulation of SSAD is of great importance to better control and operate the reactors. The modeling of SSAD reactors could be realized either by theoretical or statistical approaches.

biogas modeling CFD diffusion machine learning empirical equations

1. Anaerobic Digestion for Biogas Production

Anaerobic digestion (AD) is one of the promising solutions for recovering the energy contained in various organic wastes. Inputs to anaerobic digestion can be agricultural by-products, industrial effluents, sludge from wastewater treatment plants (WWTP) and the biodegradable fraction of household waste [1]. Depending on the dry matter content (DM) operated in digestors, there are two other types of technology: liquid-state AD (DM < 15%) and solid-state AD (DM > 15%) [2].

Liquid-state AD (LSAD), also called wet anaerobic digestion, is the technology conventionally employed by the industry. It is adapted to substrates with a relatively high water content (e.g., sewage sludge). On one hand, its humid character allows a more efficient homogenization of the mixture. On the other hand, it dilutes substrates to keep the DM level relatively low and stable in the reactors. At the end of the digestion, phase separation of digestate is generally required to (1) maintain the biomass concentration in the reactors by recirculation of its liquid phase and (2) concentrate the digestate for further agricultural usage. It should be noted that LSAD technology shows a high level of maturity. Around 90% of the AD reactors in France run in LSAD mode [3]. The disadvantage of LSAD lies on the fact of its low organic loading leading to low biogas yield rate and the high energy and financial costs for digestate phase separation and downstream treatment.

2. Solid-State Anaerobic Digestion

Although currently it does not represent a large market share, the solid-state anaerobic digestion (SSAD), also called dry anaerobic digestion, is being increasingly adopted in newly built biogas plant projects [4]. The interest of SSAD is based on the fact that it operates with a higher organic loading that gives rise to more robust biochemical reactions. Moreover, it requires less water for the dilution of the substrates upstream and consequently, less phase separation downstream. As the medium is more concentrated, solid-state digesters require less volume and less heating compared to LSAD reactors. These advantage of SSAD makes possible the construction of a low-cost biogas plant. It is also acknowledged that SSAD reactors can tolerate a relatively higher organic loading [5]. Nevertheless, the disadvantages of this type of technology are also obvious. It is less suitable for processing liquid substrates. Its solid character makes agitation very difficult, resulting in less contact between the substrates and the microorganisms. In addition, incomplete homogenization can lead to a local concentration of inhibiting compounds (e.g., ammonia, volatile fatty acids—VFA) that limit or even stop the methanogenic microbial activities [6]. Solid-state digestion, therefore, requires more sophisticated equipment (pumps, agitators, heat exchangers, etc.) for implementation. The maturity of solid-state anaerobic digestion is currently less marked than that of the LSAD process.

SSAD can be realized by various processes. Many review papers like Fagbohungbe et al. (2014) [7], Kothari et al. (2014) [8], Xu et al. (2015) [9], André et al. (2018) [3] and Franca and Bassin (2020) [10] have given comprehensive overview of various SSAD reactors available at different scales. To be general, researchers can find the continuous processes with the recirculation of liquid digestate or biogas serving as stirring methods of the solid media. Compared to continuous processes, batch reactors with discontinuous operation are more common in SSAD [11], like container-type and garage-type digesters. One has to note that the DM content is not a determining factor defining LSAD or SSAD. The solid behavior could be seen with DM content less than 15% for reactors charged by cereal straw. Media of DM content more than 15% but with sewage sludge can be pasty, an intermediary state between LSAD and SSAD.

In all cases, different from LSAD reactors, three phases are generally present in SSAD reactors: a relatively immobilized solid phase representing the bulk of solid substrates pending degradation, a liquid phase resulting from the inoculum (the leachate as well as the percolate across the solid bulk) and finally a gas phase rich in biogas found in the headspace of reactors and the pores in solid bulk (due to its characteristics similar to porous media). Depending on the technology used, the solid phases could be partially immerged in the liquid phase which is the collected at the bottom of reactors, heated through a heat exchanger and regularly sprayed to the top of bulk for a new round of percolation. This recirculation allows to maintain the operational temperature and the adequate humidity in SSAD reactors. It also helps the redistribution of the intermediate products, such as solubilized organic matter (sugars, VFA…) and alkalinity, in the solid bulk preventing the local inhibition by pH or substrates in the reactors. The useful microorganisms for biomass degradation (i.e., hydrolytics, acidogens, acetogens, and methanogens) can also be redistributed throughout the digesters by the recirculation of liquid percolate.

It has to be noted that, in reality, there exists an additional phase related to the presence of biofilm attached to the particle surface of solid phase. The microorganisms gather together as cooperative consortium by the production of extracellular polymeric substances (EPS) embedding them in the so-called biofilm [12]. Most of the microbial activities, especially those of acidogens, acetogens and methanogens, take place within this thin biofilm because only the soluble OM diffused into biofilm can be properly degraded and transformed into biogas. The behaviors of this biofilm are totally different from the solid phase since the former evolves as a function of microbial loading. Its physico-chemical properties are subject to the state of various microorganisms habiting in it. Attachment, detachment and development of biofilm can be seen during anaerobic digestion.

The presence of these four phases makes the understanding, the modeling, the operation and the control of the SSAD processes difficult.

3. Scientific Hurdles of SSAD

A SSAD reactor is generally fed with drier organic feedstock such as animal manures, silages, and green waste (fruits, vegetables, and plants), of which France has considerable production. However, in France, solid-state anaerobic digestion represents less than 9% of anaerobic digestion facilities [3]. This low presence can be explained by the lack of in-depth knowledge of the processes and the complex industrial control, as mentioned above. The scientific barriers of the sector are based on various technical aspects [3][4][8][13][14]:

- the solid feedstock leads to inefficient mixing and thus makes the medium heterogeneous in SSAD reactors;
- the pretreatment technology of lignocellulosic waste is largely studies by the scientific community but much less explored on real scale;
- the pumping of the solid inputs into SSAD reactors is not as easy as LSAD due to the special rheological properties of solid substrates (non-Newtonian media);
- the mass transfer between microorganisms and solid substrates is limited by the weak liquid/solid contact (i.e., inoculum/substrate);
- the management of local inhibitions requires hydrodynamic information in reactors,
- few robust monitoring tools are available for real-time monitoring of physico-chemical and operational parameters for accurate control;
- there is a lack of dynamic modeling tools considering different transfer phenomena and the biodegradation of OM more adapted to SSAD reactors.

4. Modeling of SSAD Processes

The SSAD processes are usually designed and operated in an empirical way [9], which is not necessarily optimized and adapted to the variation of the biomass and the change of the operational parameters. Resolving this issue calls for an efficient and accurate simulation of the biogas production kinetics from the biomass, considering numerous operational parameters as input variables. It would be one of the keys to help the deployment of SSAD technology for biomass valorization.

A large number of models were reported in the literature based on either theoretical or statistical approaches.

The theoretical approaches rely more on a predefined theory ready to explain different physics in the reactors like biokinetics of OM, mass and heat transfer, hydrodynamics and media properties. These models can be coupled so that different phenomena could be considered. **Figure 1** illustrates an example of various phenomena to be modeled in a leach-bed reactor. With experimental data one can identify the values of key parameters of these theories and then realize a simulation of the anaerobic digestion process. Intermediate results such as the evolution of physico-chemical properties (DM, VS…), VFA, pH and COD could usually be obtained and further analyzed.

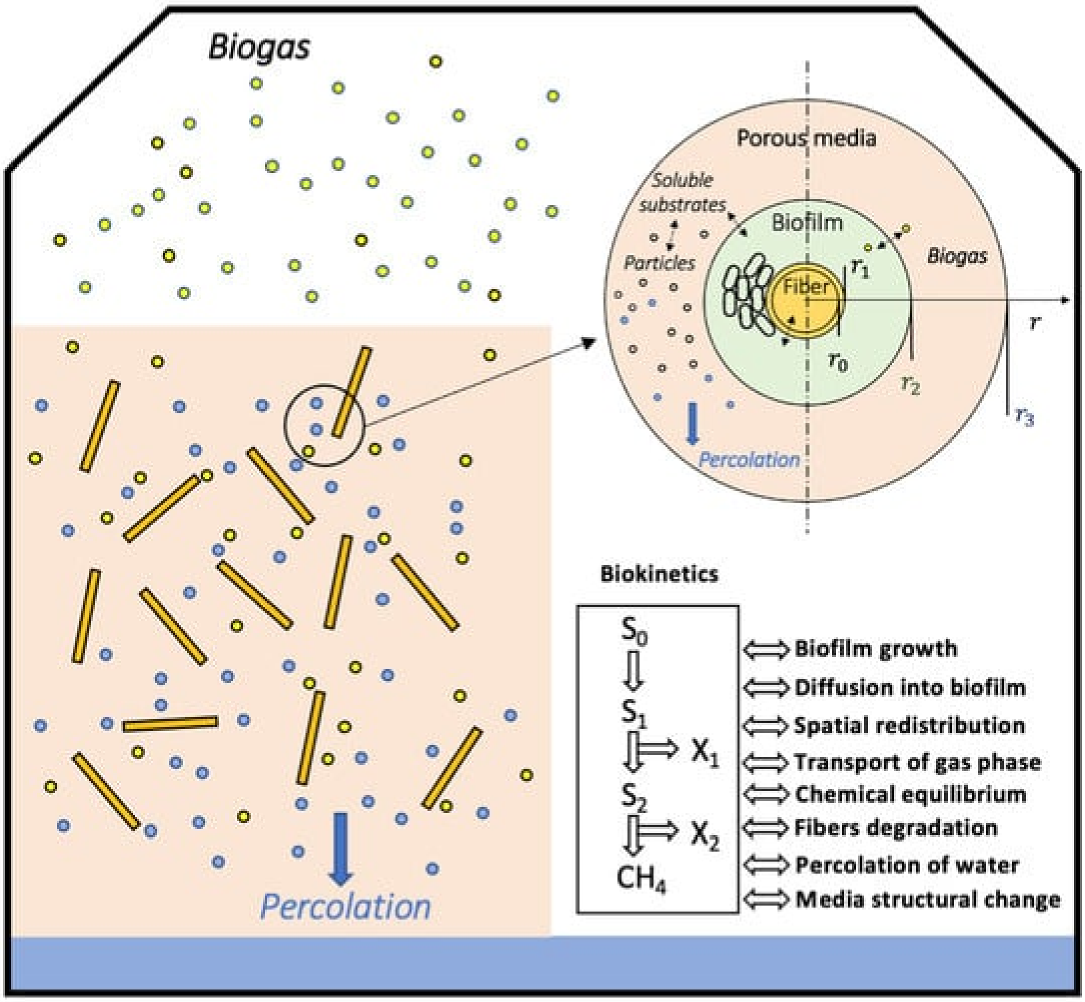

Figure 1. Multiscale simulation of a SSAD leach-bed reactor.

The statistical approaches are based more on the black box (sometimes grey box) phenomena. Researchers can either use empirical (or semi-theoretical) equations to describe the production kinetics, or employ more advanced statistical methods like machine learning method to simulate the biogas yield. Empirical or semi-theoretical equations (like the first-order kinetics and the modified Gompertz equation) are based on certain simplified theories explaining predominant physics during SSAD. Its modeling is often carried out using linear or non-linear regression of gas production curves. The statistical approaches are mostly not interested in the obtention of the intermediate results of AD. Like black box, they depend on the input parameters and accordingly return the final simulation results.

Both families of modeling are useful for the simulation of SSAD processes. The choose of the modeling methods is highly dependent on its purpose: developing a model for comprehension or a model for direct industrial applications. Many review papers on either AD or SSAD technology have contributed to a state of the art of various aspects of SSAD, from technology to its simulation [3][4][5][8][10][13]. However, since the modeling issue, especially when the complexity related to SSAD is concerned, is not the key subject of these papers, details and critical comments are not systematically given.

Wade (2020) structured the modeling methods and focused on the contribution of mathematical modeling to AD in a general way [15]. Emebu et al. (2022) studies the classification and the elaboration of various AD models. This entry describes the models according to the biochemical stages and the phenomena like mass and heat in LSAD systems [16]. The work of Xu et al. (2015) [9] is among the rare reviews commenting on the mere research advance of SSAD modeling but dated in 2015. To authors' knowledge, no comprehensive reviews since are available discussing about the SSAD numerical simulation.

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