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MODELLING OF ANAEROBIC DIGESTION - A REVIEW

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ABSTRACT

Anaerobic digesters often exhibit significant stability problems, that may be avoided only through appropriate control strategies. Such strategies require, in general, the development of appropriate mathematical models, which adequately portray the key processes that take place. This paper reviews the current state of the art in anaerobic digestion modelling, and identifies the key areas that require further research endeavors.

KEYWORDS: Anaerobic digestion, modelling, methanogenesis, biogas.

INTRODUCTION

Anaerobic digestion is a process that converts organic matter into a gaseous mixture mainly composed of methane and carbon dioxide through the concerted action of a close-knit community of bacteria. It has been traditionally used for waste treatment but there is also considerable interest in plant-biomass-fed digesters, since the produced methane is a useful source of energy.

The most common reactor type used for anaerobic digestion of wastewaters is the continuously stirred tank reactor (CSTR). The main problem of this reactor type, i.e. the fact that the active biomass is continuously removed from the system leading to long retention times, has been overcome in a number of systems based on immobilisation of the active biomass, henceforth referred to as high-rate systems.

A typical such reactor (Lettinga et al., 1980) is the Upflow Anaerobic Sludge Blanket Reactor (UASBR). In the UASBR the microorganisms are kept in the reactor due to the production of the highly flocculated, well settling, compact sludge granules which develop. Granular UASBRs are the systems of choice for low to medium-high strength wastewaters containing low or easily hydrolysable solids. Another example of a high-rate reactor is the Anaerobic Baffled Reactor (ABR), initially developed by McCarty and coworkers (Bachmann et al., 1982, 1985). This reactor consists of a series of baffled compartments where the wastewater flows upward through a bed of anaerobic sludge. The ABR does not require the sludge to granulate in order to perform effectively, although granulation does occur over time.

High-rate anaerobic reactors have the following advantages over their suspended growth counterparts:

- they operate at high solids retention times and very low hydraulic retention times (hours, when CSTRs require days);
- their design is simple;
- they are characterised by efficient heat and mass transfer;
- they require small volumes;
- they are robust to disturbances;
- biogas generation secures good mixing characteristics.

Anaerobic digestion systems are rather complex processes that unfortunately often suffer from instability. Such instability is usually witnessed as a drop in the methane production rate, a drop in the pH, a rise in the volatile fatty acid (VFA) concentration, causing digester failure. It is caused by (a) feed overload, (b) feed underload, (c) entry of an inhibitor, or (d) inadequate temperature control. The usual remedy, is a rapid increase in the HRT (hydraulic retention time), and when this fails, the digester has to be primed with sludge from a "healthy" digester. This, however, may be quite costly, in view of the fact that anaerobic digestion is a very slow process.

In order to be able to design and operate efficiently anaerobic digestion systems, appropriate mathematical models need to be developed. The International Association for Water Quality (Anaerobic Digestion Specialist Group) formed in 1997, at Sendai, Japan, an international task force for developing an appropriate modelling framework for anaerobic digestion. The objective of this communication is to review existing models for anaerobic digestion systems and to identify the areas that require further development.

EXISTING MODELS OF ANAEROBIC DIGESTION

Anaerobic digestion is a multistep process involving the action of multiple microbes. Usually, such processes contain a particular step, the so called rate-limiting or rate-determining step, which, being the slowest, limits the rate of the overall process (Hill, 1977). Lawrence (1971) defined as limiting step "that step which will cause process failure to occur under imposed conditions of kinetic stress". The first attempts for modelling anaerobic digestion led to models describing only the limiting step. However, during a wide range of operating conditions, the limiting step is not always the same. It may depend on wastewater characteristics, hydraulic loading, temperature, etc. (Speece, 1983). Andrews (1969, 1971) for example considered acetogenic methanogenesis as the limiting, O'Rourke (1968) the conversion of fatty acids to biogas, and Eastman and Ferguson (1981) the hydrolysis of biodegradable suspended solids.

It is apparent that the "limiting step hypothesis" leads to simple and readily usable models. Such models, however, do not describe very well the digester behaviour, especially under transient operating conditions.

In the sequel we give a brief description of the key anaerobic digestion models that have been developed so far for describing suspended growth systems.

The Graef and Andrews model (1974) involves only the acetoclastic methanogens. The conversion of fatty acids into biogas is considered limiting. Volatile fatty acids are expressed as acetic acid and the methanogens composition is assumed to be $C_5H_7NO_2$. The overall reaction, according to this model, may be represented as follows:

$$CH_3COOH + 0.032\ NH_3 \rightarrow 0.032\ C_5H_7NO_2 + 0.92\ CO_2 + 0.92\ CH_4 + 0.096\ H_2O \quad (3)$$

Monod kinetics with substrate inhibition are assumed (Andrews, 1969), i.e.

$$\mu = \frac{\mu_{max}}{1 + \frac{K_S}{S} + \frac{I}{K_i}} \quad (2)$$

where μ is the specific growth rate, μ_{max} is the maximum specific growth rate, K_S is the half-velocity constant, S is the concentration of growth-limiting substrate, K_i is the inhibition constant and I is the inhibitor concentration.

Undissociated acetic acid is considered as the limiting substrate S, and as the inhibitor as well. Its concentration is determined based on the equilibrium assumption of the acetic acid dissociation reaction. The pH is estimated by a total ion balance. According to this model, a digester is expected to fail whenever, for some reason, the fatty

Table 1. Models that assume substrate inhibited Monod kinetics (Andrews, 1969) of the methanogens

Model	bacterial group (substrates)	processes	kinetics (function of)	accounted inhibition
Graef and Andrews (1974)	acetoclastic methanogens (unionised VFA as acetate)	methanogenesis	Andrews	unionised VFA or an external inhibitor
Hill and Barth (1977)	acid formers (glucose)	hydrolysis of insoluble organics and acidogenesis	Andrews (temperature)	unionised VFA
	methane formers (unionised VFA as acetate)	methanogenesis	Andrews (temperature)	unionised VFA and unionised NH_3
Kleinstreuer and Powegha (1982)	acid formers (soluble organics)	acetogenesis	Andrews (temperature, pH)	unionised acetate toxic substances
	methane formers (acetate)	methanogenesis	Andrews (temperature, pH)	unionised acetate toxic substances
Moletta et al. (1986)	acidogenic bacteria (glucose)	acetogenesis	Andrews	unionised acetate
	methanogenic bacteria (acetate)	methanogenesis	Andrews	unionised acetate
Smith et al. (1988)	(rapidly degradable biomass)	hydrolysis	First order	
		hydrolysis	First order	
	(slowly degradable biomass)	acidogenesis	First order	total VFA
	acidogenic bacteria (soluble organic matter)	methanogenesis	Andrews	unionised VFAs
	methanogenic bacteria (unionised VFAs)			

acid concentration is increased. This causes a drop in the pH and a rise in the concentration of undissociated acetic acid concentration. This in turn causes a drop in the growth rate of the methanogenic population, until they are washed out, if the situation is prolonged. The Graef and Andrews model can also predict the digester response to the entry of an external inhibitor.

An anaerobic digester is essentially a three-phase system. The model assumes a gas phase in contact but not in equilibrium with the liquid phase. Gas phase is assumed to obey the ideal gas law. Methane is assumed to be water insoluble and directly transferable to the gas phase, whereas the generated CO_2 partly dissolves in the liquid phase giving carbonic acid, which depending on the pH is dissociated giving bicarbonate and carbonate ions, and partly escapes to the gas phase at a rate given by the equation:

$$T_G = K_L (K_H P_{CO_2} - [CO_2]_D) \qquad (3)$$

where T_G is the CO_2 transfer rate from gas phase to liquid, K_L is the mass transfer coefficient, K_H is Henry's constant, P_{CO_2} is the CO_2 partial pressure and $[CO_2]_D$ is the dissolved CO_2 concentration.

Table 2. Models that assume substrate inhibited Monod kinetics (Andrews, 1969) at the methanogenesis

model	limiting step	predicted causes of digesters failure	suitable for the digestion of
Graef and Andrews (1974)	methanogenesis	VFA accumulation	soluble organic matter
Hill and Barth (1977)	methanogenesis	heavy organic loading VFA accumulation	animal waste
Kleinstreuer and Powegha (1982)	methanogenesis	heavy organic loading VFA accumulation	various substrates
Moletta et al. (1986)	methanogenesis	----------	easily fermentable substrates
Smith et al. (1988)	methanogenesis	VFA accumulation	biodegradable organic particulate

Graef and Andrews used their model for simulating digester startup, and digester response to organic and hydraulic overloading, and entry of an inhibitor. To date, no experimental verification of this model has been made.

Other models (Tables 1 and 2) that also assume substrate inhibited Monod kinetics (Andrews) of the methanogens are:

- Hill and Barth (1977) who also considered hydrolysis, acidogenesis and ammonia inhibition (Fig. 1).
- Kleinstreuer and Powegha (1982), which involves hydrolysis of biodegradable solids, acetogenesis and methanogenesis, dependent on pH and temperature (Fig. 2).
- Moletta et al. (1986) which involves also an acidogenesis step, that forms acetate from glucose, and are inhibited by undissociated acetic acid (Fig. 3).
- Smith et al. (1988). A slow and a fast hydrolysis step are assumed, whereas acidogenesis of the soluble intermediates and methanogenesis are also taken into account (Fig. 4).

The model of Hill (1982) assumes that methanogenesis depends on the total fatty acids. This model was specially developed for describing digestion of manure and animal wastes. The model assumes inhibition by the total fatty acid concentration (Tables 3, 4). The following bacterial groups are assumed to participate in the overall digestion process (Fig. 5): a) acidogenic, which grow on glucose (considered as the dissolved organics less the volatile fatty acids) form a mixture of acetic, propionic and butyric acids, b) hydrogenogenic, which have a slow growth rate, convert propionic and butyric acid into acetic acid and H_2, c) homoacetogenic produces acetate from H_2 and CO_2, d) H_2-methanogenic reduces CO_2 into CH_4 and e) acetate-methanogenic converts acetic acid into biogas (CH_4 and CO_2). All five steps are assumed to be inhibited by high fatty acid concentrations. This inhibition is expressed both in the growth rate and microbial decay rate expressions. According to this model, anaerobic digestion is stalled, whenever an accumulation of VFAs is brought about. In particular, inhibition causes a decrease in the rate of VFA consumption, leading

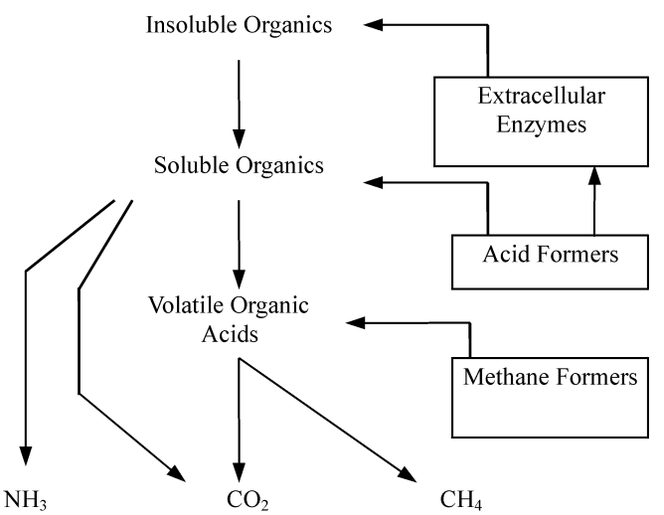

Figure 1. Block diagram of Hill and Barth (1977) mathematical model

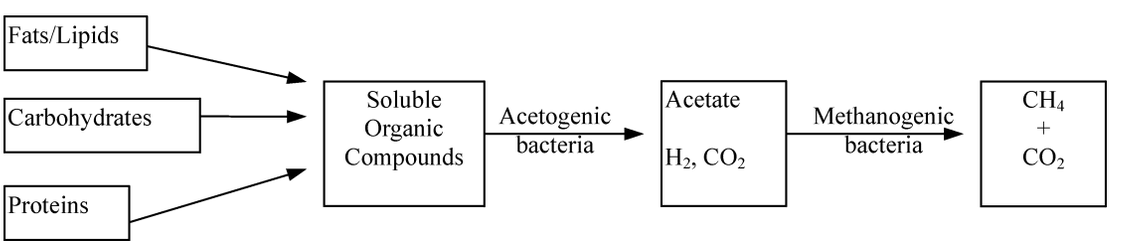

Figure 2. Schematic biochemical process stages of anaerobic digestion (Kleinstreuer and Powegha, 1982)

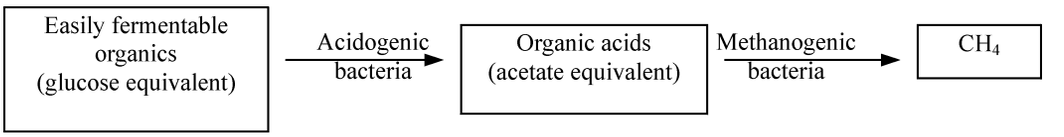

Figure 3. Flow chart of Moletta et al. (1986) model

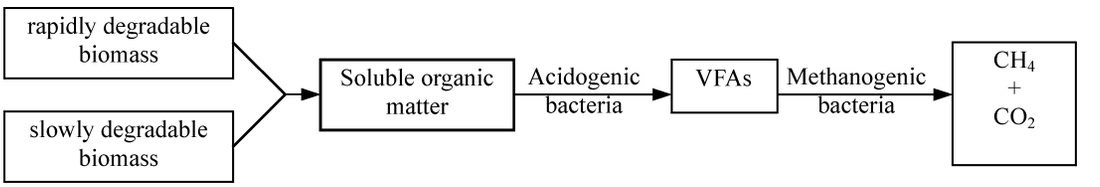

Figure 4. Flow chart of Smith et al. (1988) model

into acid accumulation. Above a certain critical VFA concentration, the digester fails regardless of the pH value. This model is based on specific stoichiometric reactions for each of the five key reaction steps. As most stoichiometric coefficient and several kinetic rates were unavailable from the literature, these parameters were estimated through fitting of pilot-scale and full-scale anaerobic digesters.

Another model, which also considers total volatile fatty acid concentration as a key parameter (Tables 3 and 4) but also accounts for the influence of other parameters such as the pH, is that of Bryers (1985) (Fig. 6).

Table 3. Models that consider total volatile fatty acid concentration as a key parameter

Model	bacterial group (substrates)	processes	kinetics (function of)	accounted inhibition
Hill (1982)	acidogenic bacteria (glucose)	acidogenesis	Monod based	total VFA
	hydrogenogenic bacteria (total propionate and butyrate)	acetogenesis	Monod based	total VFA
	homoacetogenic bacteria (H_2 and CO_2)	homoacetogenesis	Monod based	total VFA
	H_2 methanogenic bacteria		Monod based	total VFA
	(H_2 and CO_2)	methanogenesis		
	acetate methanogenic bacteria (total acetate)	Monod based methanogenesis	total VFA	
Bryers (1985)	(insoluble organic matter)	hydrolysis	first order	
	acid forming bacteria (aminoacids, simple sugars, fatty acids)	acidogenesis	Monod	
	propionic acid utilising bacteria (total propionic acid)	acetogenesis	Monod	
	methanogenic bacteria (total acetic acid, hydrogen)	methanogenesis	Monod (pH)	

Table 4. Models that consider total volatile fatty acid concentration as a key parameter

Model	limiting step	predicted causes of digesters failure	suitable for the digestion of
Hill (1982)	acetogenesis	VFA accumulation	animal waste
Bryers (1985)	acetogenesis	VFA accumulation	biodegradable organic particulate

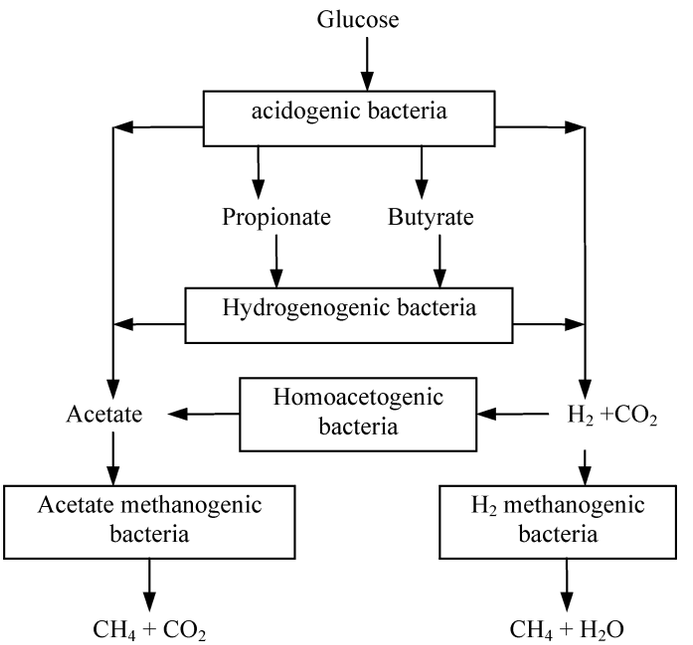

Figure 5. Flow chart of Hill (1982) model

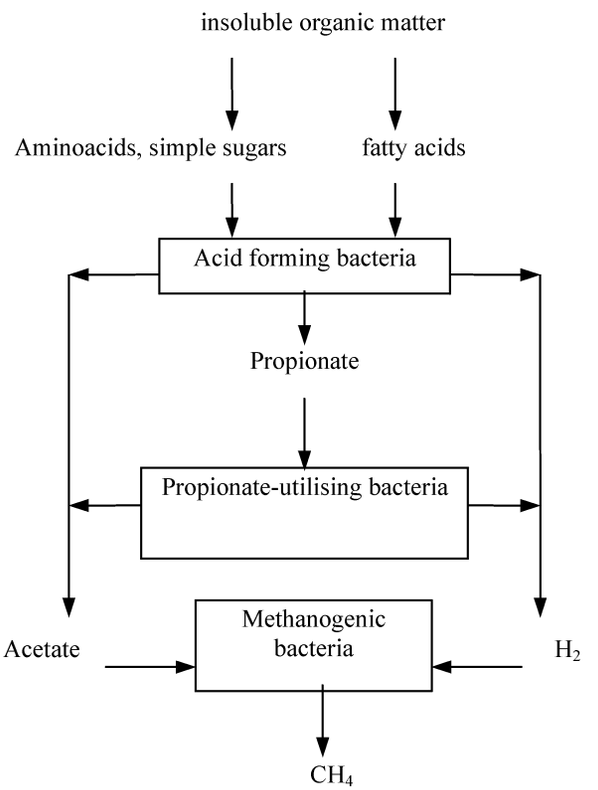

Figure 6. Flow chart of Bryers (1985) model

Mosey (1983) considered the hydrogen partial pressure as the key regulatory parameter of the anaerobic digestion of glucose (Tables 5, 6). This influences the redox potential in the liquid phase. The model considers four bacterial groups (Fig. 7) to participate in the conversion of glucose to CO_2 and CH_4: a) the acid-forming bacteria, which are fast-growing and ferment glucose to produce a mixture of acetate, propionate and butyrate, b) the acetogenic bacteria convert the propionate and butyrate to acetate, c) the acetoclastic methane bacteria convert acetate to CO_2 and CH_4, and d) the hydrogen-utilising methane bacteria reduce CO_2 to CH_4. The fatty acid relative production is assumed to depend on the redox potential or equivalently, on the ratio [NADH]/[NAD+]. This ratio is made a function of the hydrogen partial pressure in the gas phase.

Considering that the acidogenic bacteria follow the glycolytic metabolic pathway, the factor that regulates the relative amounts of fatty acid generation is the liquid phase redox potential, or equivalently the ratio [NADH]/[NAD+] inside the bacterial mass. This ratio may be expressed as a function of the hydrogen partial pressure, based on the following assumptions:

1. Inside the bacteria, a neutral pH is maintained, despite variations in the liquid medium.

Table 5. Models using H_2 as the control parameter

Model	bacterial group (substrates)	processes	kinetics (function of)	accounted inhibition
Mosey (1983)	acid-forming bacteria (glucose)	acidogenesis	Monod (pH)	H_2 partial pressure
	propionic acid bacteria (propionate)	acetogenesis	Monod (pH)	H_2 partial pressure
	butyric acid bacteria (butyrate)	acetogenesis	Monod (pH)	H_2 partial pressure
	acetoclastic methane bacteria (acetate)	methanogenesis	Monod (pH)	
	hydrogen-utilising methane bacteria (H_2 and CO_2)	methanogenesis	Monod (pH)	
Pullammanappallil et al. (1991)	acidogenic bacteria (glucose)	acidogenesis	Monod (H2)	
	propionate-utilising acetogens (propionate)	acetogenesis	Monod	H_2 partial pressure
	butyrate-utilising acetogens (butyrate)	acetogenesis	Monod	H_2 partial pressure
	acetoclastic methane bacteria (acetate)	methanogenesis	Andrews	unionised propionate and butyrate
	hydrogen- utilising bacteria (H_2 and CO_2)	methanogenesis	Monod (pH)	
Costello et al. (1991)	acid-forming bacteria (glucose)	acidogenesis	Monod	H_2 partial pressure pH products
	lactic acid bacteria (lactate)	acidogenesis	Monod	H_2 partial pressure pH products
	propionic acid bacteria (propionate)	acetogenesis	Monod	H_2 partial pressure pH products
	butyric acid bacteria (butyrate)	acetogenesis	Monod	H_2 partial pressure pH products
	acetoclastic methane bacteria (acetate)	methanogenesis	Monod	pH
	hydrogen-utilising methane bacteria (H_2 and CO_2)	methanogenesis	Monod	pH

2. Hydrogen gas is freely and rapidly diffused through the bacterial membrane, so that its partial pressure inside the cell is the same as its partial pressure in the digester gas phase.

3. The redox potential inside the cell is equal to that of the liquid medium.

Apart from the acidogenic bacteria, hydrogen partial pressure also influences the acetogenic growth rate, since high values inhibit (thermodynamically) the generation of propionic and butyric acids. Finally, low pH values (< 6) are expected to be inhibitory to all the bacterial species. According to the Mosey model, a sudden increase in the organic loading rate is expected to cause an accumulation of VFAs, since the acetogens grow at a slower rate than the acidogens. The subsequent drop in the pH inhibits in turn the hydrogen utilising methanogenic bacteria, causing a rise in the hydrogen partial pressure, which causes further accumulation of propionic and butyric acids. Methane generation is stalled when the pH drops to particularly low levels (< 5.5).

Table 6. Models using H_2 as the control parameter

Model	limiting step	predicted causes of digesters failure	suitable for the digestion of
Mosey (1983)	acetogenesis	sudden increase in the organic loading rate	glucose
Pullammanappallil et al. (1991)	acetogenesis and/or methanogenesis	overloading	glucose
Costello et al. (1991)	acetogenesis	overloading	soluble carbohydrates

Based on the work of Mosey followed the models of Pullammanappallil et al. (1991) and Costello et al. (1991a, 1991b) (Tables 5, 6). Pullammanappallil et al. (1991) (Fig. 7) allowed description of the gas phase and acetoclastic inhibition by undissociated fatty acids. Costello et al. (Fig. 8) assumed that glucose is first converted into acetic, butyric and lactic acids, followed by conversion of lactate into propionate and acetate by another bacterial group.

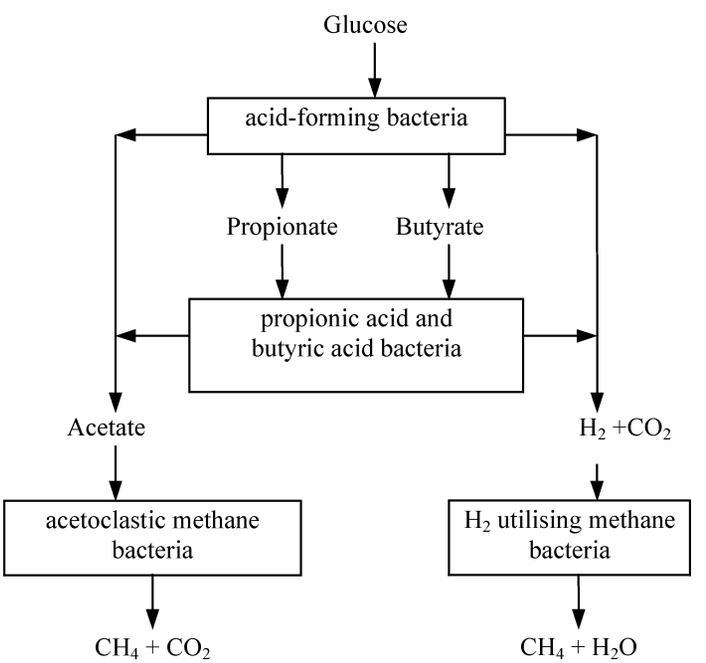

Figure 7. Flow chart of Mosey (1983) and Pullammanappallil et al. (1991) models

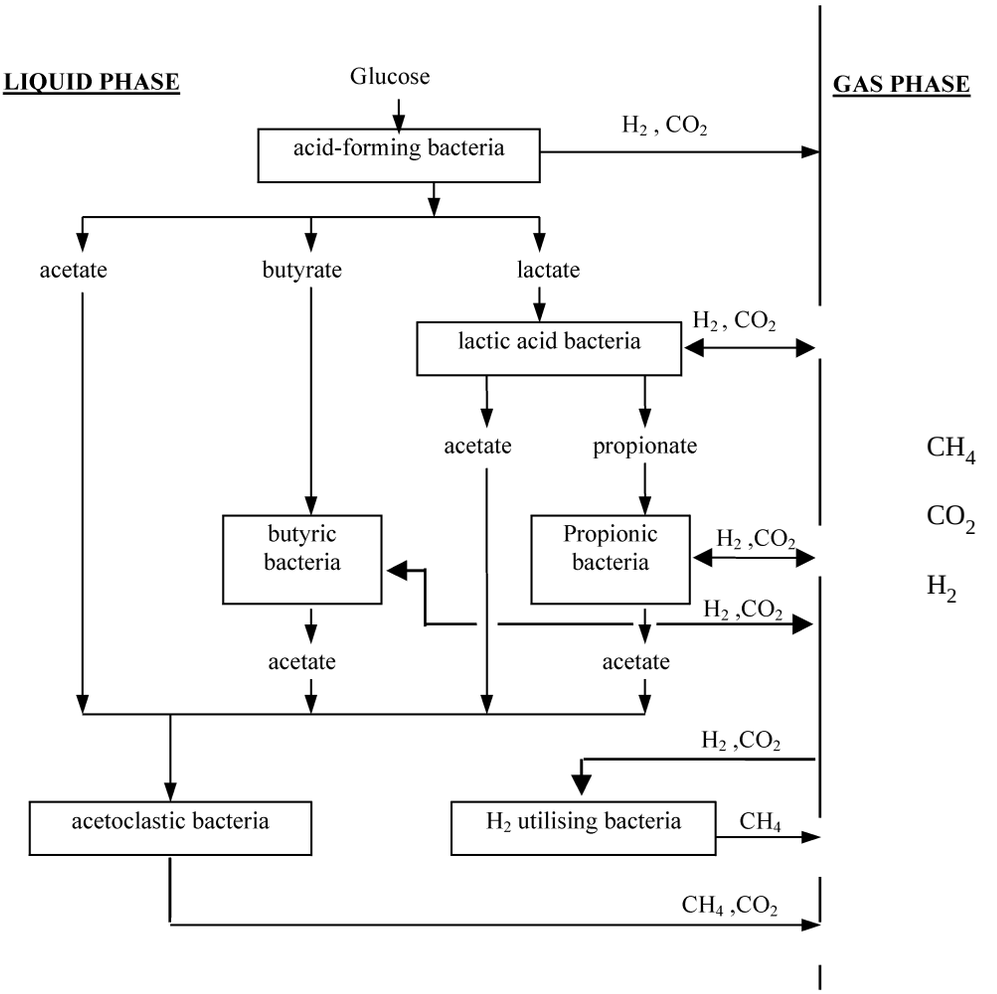

Figure 8. A schematic of the relationships between each group of bacteria in the anaerobic ecosystem model (Costello et al., 1991)

All the models described thus far are capable of predicting digester failure, caused by a specific disturbance, either through a drop in the pH, and/or through accumulation of volatile fatty acids. Such is a commonly observed behaviour in digesters treating municipal sludge and/or high organic content industrial wastewaters. None of these models, however, can adequately describe anaerobic digestion of manure (Angelidaki, 1992). Digesters fed with manure, exhibit a self-regulation of the pH, attributed to the generated ammonia. The model of Angelidaki et al. (1993) considers hydrolysis, acidogenesis, acetogenesis and methanogenesis (Fig. 9). Free ammonia is assumed to inhibit methanogenesis, acetic acid is assumed to inhibit acetogenesis, and total VFA is assumed to inhibit acidogenesis (Table 7). The maximum specific growth rate of the bacteria and the degree of ionisation of ammonia are assumed to depend on the temperature and the pH. The pH self-regulation mechanism is as follows. Whenever free ammonia (high for high pH) inhibits methanogenesis, acetic acid is accumulated. This causes an inhibition to acetogenesis, and a consequent accumulation of propionic and butyric acids, leading to inhibition of acidification. The model is very good for describing the behaviour of manure fed digesters. VFA accumulation reduces the pH, causing a decrease in the free ammonia concentration and the inhibition of methanogenesis. The process is thus self-regulatory, unless the magnitude of the disturbance is larger than the system can withstand. When this occurs, the pH drops significantly, causing digester failure (Table 8).

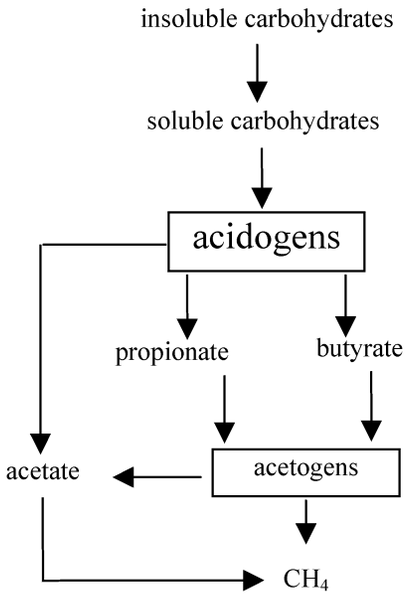

Figure 9. Flow chart of Angelidaki et al. (1993) model

Table 7. More complicated models

Model	bacterial group (substrates)	processes	kinetics (function of)	accounted inhibition
Angelidaki et al.	(insoluble carbohydrates)	enzymatic hydrolysis	first order	
	acidogens (soluble carbohydrates)	acidogenesis	Monod (temperature, pH)	total VFA
	acetogens (propionate and butyrate)	acetogenesis	Monod (temperature, pH)	acetate
	acetoclastic methanogens (acetate)	methanogenesis	Monod (temperature, pH)	free NH_3
Siegriest et al. (1993)	(biopolymers)	hydrolysis	first order (temperature)	
	acidogens (aminoacids and sugars)	fermentation of aminoacids and sugars	Monod (temperature)	
	acetogens (fatty acids)	anaerobic oxidation of fatty acids	Monod (temperature)	H_2 partial pressure acetate
	acetogens (propionate)	anaerobic oxidation of propionate	Monod (temperature)	H_2 partial pressure acetate
	acetoclastic methanogens (acetate)	acetate conversion to methane	Monod (temperature)	pH free NH_3
	hydrogen-utilising methanogens (H_2 and CO_2)	hydrogen conversion to methane	Monod (temperature)	pH pH

Table 8. More complicated models

Model	limiting step	predicted causes of digesters failure	suitable for the digestion of
Angelidaki et al. (1993)	acetogenesis	pH break down	manure
Siegriest et al. (1993)	acetogenesis	rise of NH_3 content of the feed hydraulic load increase	sludge

More complicated model that take into account ammonia inhibition, lysis and hydrolysis of cell biomass, description of a physical-chemical system of pH-level, including the main buffer systems, is that of Siegriest et al. (1993) (Tables 7, 8, Fig. 10).

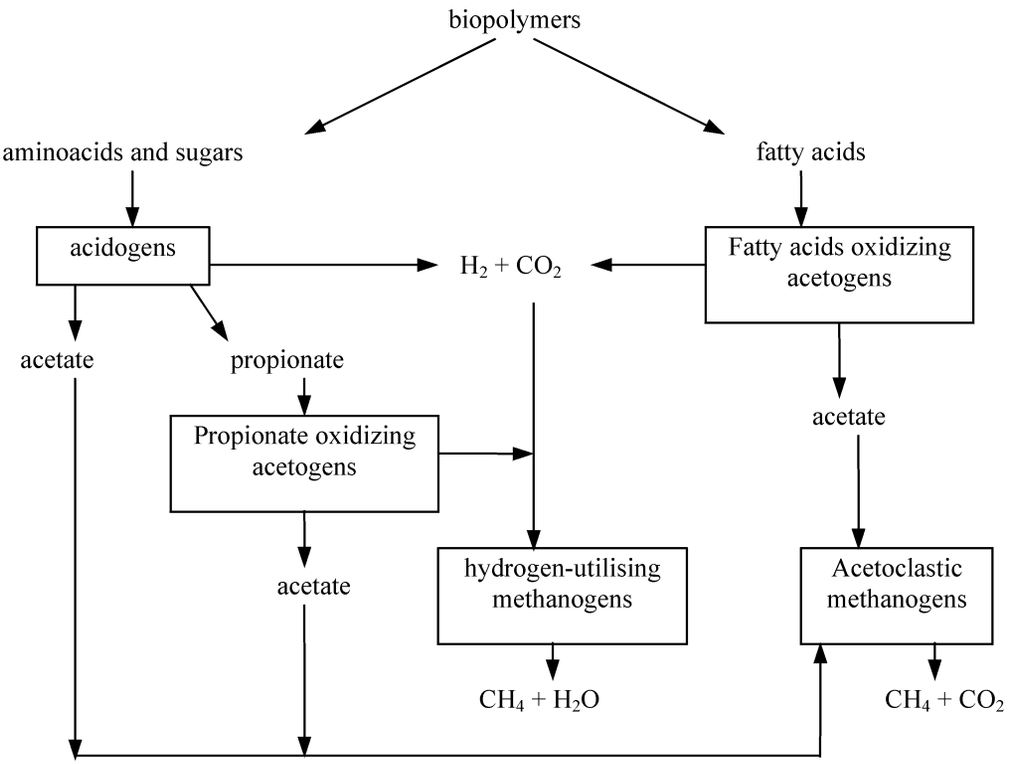

Figure 10. Flow chart of Siegriest et al. (1993) model

All models described so far consider organic matter as a whole and do not account for the nature of the organic macromolecules in the feed composition. A modelling approach that takes the complex feed composition (breakdown in carbohydrate, protein, VFAs and other organics) into account has been recently proposed (Gavala et al., 1996). Some of the mechanisms involved in the hydrolysis and biodegradation of complex organic molecules were already elucidated but there was no appropriate kinetic modelling framework available. Thus, it was known that lipids are first hydrolysed into glycerol and long-chain fatty acids (LCFAs). The LCFAs are further degraded into acetate and hydrogen (Weng and Jeris, 1976). Acetate and hydrogen are then finally converted to biogas (Bryant, 1979). Lipids can cause inhibition of the process (Angelidaki and Ahring, 1992). However, it was shown in this work that over 80% of added lipid was degraded to biogas after an adaptation period, by codigestion of lipids and manure. Degradation of protein containing wastes gives rise to a disturbance to the digester. After an adaptation period this waste can also be degraded (Ahring et al., 1992). The model of Gavala et al. (1996) describes the codigestion process of agroindustrial wastewaters. It is assumed that the wastewaters consist of carbohydrates and proteins (undissolved and dissolved) and other dissolved organic matter. The conversion of organic matter to biogas is carried out by the simultaneous action of three groups of bacteria: acidogens (hydrolysis and acidogenesis), acetogens and methanogens. In the hydrolysis step, the undissolved carbohydrates and proteins are hydrolysed to dissolved carbohydrates and proteins, respectively; in the acidogenesis step, the dissolved carbohydrates, proteins and other organic matter are converted to acetate and propionate; while in the acetogenesis step, propionic acid is converted to acetate. Finally,

methane is produced by acetoclastic methanogens. Hydrolysis of undissolved proteins and carbohydrates is assumed to proceed with first-order kinetics, while Monod kinetics are assumed for the acidogenesis, acetogenesis and methanogenesis steps. The consumption of propionate and acetate proceeds under substrate inhibition. The model is capable of predicting adequately the COD and fatty acids dependence on the operating conditions, and should be useful for designing codigestion processes (Lyberatos et al.,1997).

All the existing detailed anaerobic digestion models do not take into account the particular nature of the developed granular sludge in high rate systems, such as an Upflow Anaerobic Sludge Bed Reactor (UASBR) or an Anaerobic Baffled Reactor (ABR). Some kind of a general approach was suggested for modelling of a UASB reactor (Kalyuzhnii and Fedorovich, 1997).

During the last 20 years, significant research effort has been invested in the understanding of granule formation in high-rate systems, such as the UASB. Although the precise mechanism of granule formation still remains unknown, their composition and the factors influencing their formation are understood to a great extent. The granules contain bacteria in a 3-D array. The exact bacterial types depend on the wastewater composition (Lettinga et al., 1980; Hulshoff Pol et al., 1982; 1983; Brummeler et al., 1985; Wu et al., 1987; MacLeod, 1990; Vissier et al., 1991; Grotenhuis et al., 1991; Bitton, 1994). The factors that influence the formation of granules are (Lettinga et al., 1979; Lettinga et al., 1980; Hulshoff Pol et al., 1983; Wu et al., 1987):

- Digester startup conditions
- Degree of acclimation to the fed wastewater
- Hydraulic loading
- Organic loading
- Biogas production per unit volume
- Concentration of inhibitors
- Availability of nutrients
- Cation concentration, especially Ca^{2+} and Mg^{2+}
- Concentration and type of suspended solids contained in the wastewater.

These factors, should be evaluated from a modelling point of view, and the effect of the significant ones should be properly accounted for.

NEW DIRECTIONS

The models developed so far address several aspects that are considered particularly important for describing the behaviour of anaerobic digesters. These models have been, to a varying degree, successful in predicting digester operation, failure and possible remedies. In our opinion, as has been recognised by the IAWQ, the times are mature enough to consider developing a general framework that will (a) consolidate the important features that have been described so far, and (b) help direct and focus future research endeavors. In this process, we believe four significant issues need to be addressed:

(a) A key step in the overall anaerobic digestion process is the hydrolysis of the organic compounds into soluble intermediates, a step that in certain circumstances may well be the rate-determining step of the process. Significant amount of information has been published on the kinetics of hydrolysis. In most cases, the experimental data have not been used for the development of appropriate kinetic models. In other instances, hydrolysis of various macromolecules has been considered in anaerobic environments that do not involve methanogenesis. The same is true for acidogenesis. Sludge acidogenesis is a good example. There is therefore a need for development of a sufficiently general framework as a standard for the hydrolysis and acidogenesis steps that will allow proper exploitation of past information and appropriate focusing of future research endeavors.

(b) The key physicochemical (effect of pH, temperature, gas-liquid phase mass transfer) and biochemical processes (acetogenesis, methanogenesis) that have been adequately described through the existing models for soluble substrate bioconversion, need to be incorporated in an overall model, the structure of which will be agreed upon, that could adequately describe these steps under a wide range of operating conditions (such as pH values, ammonia availability, retention times and organic loading rates).

(c) The effect of several inhibitors (oxygen, chloroform, halogenated organics, heavy metals, etc.) has been studied by several investigators. Again, however, the available information is not properly quantified in the form of a model, that could be used to predict digester response upon exposure to such inhibitors.

(d) Heterogeneous systems, such as high-rate granular systems and systems that allow biomass retention through other means (contact stabilisation, anaerobic filters, fluidised beds, packed beds, hybrid systems, membrane reactors), represent an additional significant challenge to the modeller. Significant insight may be gained here through modelling approaches in other fields (such as heterogeneous chemical reactors).

These steps will allow appropriate anaerobic digestion models that can be used to design and efficiently operate anaerobic digestion systems.

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