

A method for the in-situ thermal-alkaline treatment of organic waste to enhance anaerobic solids degradation and biogas generation

Field of Invention

This invention relates to an improved method of treatment of organic waste and enhances the degradation of biosolids and biogas generation in an anaerobic digestion system. For example, this invention relates to an improved method of sludge treatment to enhance the degradation of biosolids and biogas generation in an anaerobic digestion system.

Background of the Invention

The listing or discussion of a prior-published document in this specification should not necessarily be taken as an acknowledgement that the document is part of the state of the art or is common general knowledge.

Sludge treatment in a wastewater treatment plant (WWTP) can consume some 50% of the total operating costs. Many WWTPs apply anaerobic digestion to degrade organic matter in the sludge and generate biogas so as to recover energy. The organic sludge stream is hydrolysed, and thereafter undergoes acidogenesis and methanogenesis. Acidogenesis results in volatile fatty acids (VFAs), carbon dioxide (CO₂), and smaller quantities of hydrogen (H₂) while methanogenesis results in carbon dioxide and methane (CH₄). In a conventional single stage system, the pH for hydrolysis is about 7, while in a conventional 2-phase system, the pH value is normally less than 6.

While the anaerobic digestion is phased in nature, the anaerobic digesters used in conventional sludge digestion process are typically single-stage. However, a completely phased anaerobic process is difficult to achieve in practice although, if successful, it can possibly achieve high percentage conversion and high rates of organic stabilization and gas production. It is generally assumed that acidogenesis is optimized at a pH that is less than 6.5, while methanogenesis is predominant at about pH 7. Therefore, in a single phase system, a single stream of biogas is generated that combines the CO₂ from acidogenesis with the CO₂ and CH₄ from methanogenesis. In such systems, the pH of the system must be carefully controlled because methanogenesis is sensitive to both low and high pH values, meaning that the pH needs to be maintained in a range of from 6.5 to 7.5.

A 2-phase anaerobic digestion system and/or process has been used to separate the hydrolysis/acidogenesis reaction from the acetogenesis/methanogenesis reaction, allowing each reaction to operate at lower pHs and at neutral pH to below 8.0, respectively. This approach allows for optimization of operating conditions for acidogenesis and methanogenesis separately, and thus optimizes the conditions to sustain specific microbes involved in the different stages of the conversion of material to biogas. These two stages take place simultaneously in two different reactors and provide the optimal conditions for acidogens and methanogens, thus enhancing the performance of the overall system, which includes organic degradation, and more specifically, methane production and carbon dioxide fixation. However, it has been noted in the laboratory and at full-scale installations that complete phase separation (i.e. full separation of the acidogenic and methanogenic phases) has not been achieved. This means that the gas from the acidogenic phase will contain a little CH_4 (< 20%).

In the acidogenic phase, the primary objective is conversion of biodegradable organics to volatile fatty acids (VFAs). The acidogens responsible for VFA conversion are predominantly present in acidogenic sludge, which includes:

- (1) fermentative bacteria which are responsible for the production of VFA;
- (2) hydrogen producing acetogenic bacteria, which metabolizes propionic acid, other VFAs and alcohols into acetate and H_2 ; and
- (3) homoacetogens which use H_2 and CO_2 to produce acetate.

In the methanogenic phase, VFAs produced in the acidogenic phase are consumed to produce methane and carbon dioxide.

Anaerobic digestion of sludge is often hampered by the large size of the organic particulates and microbial cell walls (especially if the feed sludge contained secondary sludge). Consequently, hydrolysis of sludge particulates can become the overall rate limiting step of the entire process in either the single stage or 2-phase reactors mentioned above. In order to improve the kinetics of hydrolysis, various pre-treatment methods to disintegrate the sludge and microbial cell walls have been developed. These methods include ultrasonic treatment, ozone oxidation, alkaline treatment, the Fenton process and enzymatic treatment.

Compared to the other methods, alkaline treatment has several advantages, such as the use of simple devices, ease of operation and its high efficiency. Using a higher dosage of alkaline materials in the pre-treatment would result in a higher reduction in solids and a higher pH in the treated sludge. However, although the VFAs content can be significantly

increased after alkaline treatment, the high pH of the treated sludge can inhibit the following methanogenesis step. The consequent high concentration of total dissolved solids (TDS) following alkaline treatment can also inhibit the microbes. The common practice is to use acid to neutralize the alkaline materials and reduce the pH before feeding the treated sludge into an anaerobic system. This increases the cost of the sludge treatment.

Hence, a typical 2-phase anaerobic system requires strict pH control (with a low pH process leading to an above-neutral pH process) to separate the acidogenic from the methanogenic process in order to provide the anticipated better performance. The alkaline pretreatment would then require acid neutralisation to bring the pH down before methanogenesis.

Heat treatment of sludge has also been shown to be effective as a pre-treatment. Various temperatures, ranging from 60 to 270 °C, have been reported in the literature. Under such treatment, the sludge's proteins and carbohydrate will be released up to 60°C, beyond which further release would be limited.

There are existing methods for thermal-alkaline pre-treatment of waste sludge. These methods are chemical processes and are applied at very high pH values (10-12) and temperatures to improve the efficiency of sludge degradation. Additional chemicals are then required to neutralize the pH before feeding the pretreated sludge into an anaerobic digester, leading to increased material and energy costs.

Given the above, there remains a need to provide improved processes for wastewater treatment.

Summary of Invention

Surprisingly, the strict pH control used in conventional 2-phase anaerobic systems is not necessary to treat organic waste, for example produced in the treatment of oily sludge, oily wastewater, food waste, industrial sludge, sewage sludge and, particularly, wastewater (i.e. sludge from wastewater treatment). In contrast with the typical leading reactor in 2-phase systems, operating the leading reactor of a 2-stage system under alkaline conditions results in better solid reduction performance, more consistent production of CH₄ and improved VFAs production.

The 2-stage system only requires a slight pH adjustment after pretreating the sludge, so the cost associated with the use of extra chemicals is reduced. The lower pH values and

temperatures used in the 2-stage process of the current invention are possible because the process combines chemical action with biological enzymatic action to achieve hydrolysis and subsequent acidogenesis. These milder conditions allow the discharge/effluent of the first stage to be fed to the second primarily methanogenic reactor with minor or no pH correction and without temperature correction. Having milder operating conditions in the first reactor may enable a population of methanogens to survive within it and use the metabolites produced in the acidogenesis step (e.g. H_2 , CO_2 and VFAs) to generate CH_4 . The presence of this methanogenic population in the first reactor may enhance the production of metabolites from the acidogenesis step by enabling the concentration of H_2 , CO_2 and VFAs to be controlled at a level that will not inhibit further production of said metabolites and the existence of such methanogens may also enhance methane production in the first stage by converting H_2 and CO_2 into CH_4 .

Thus, in a first aspect of the invention, there is provided a process for the treatment of organic waste comprising the steps of: introducing a feed stream comprising organic waste into a first reactor; generating an effluent from the first reactor; and providing the effluent from the first reactor to a second reactor, wherein the first reactor is maintained at a pH of from about 6.5 to about 10.0.

In an embodiment of the invention, the first reactor is provided upstream of the second reactor.

In a further embodiment of the invention, first reactor is maintained at a pH of from about 7.0 to about 9.0. For example, the first reactor may be maintained at a pH of from about 7.5 to about 8.5, such as at about 8.0.

In yet a further embodiment of the invention, the first reactor is primarily a hydrolysis/acidogenic reactor. In a still further embodiment of the invention, the second reactor is primarily a methanogenic reactor or is a single stage anaerobic reactor.

In yet a further embodiment of the invention, the second reactor or, more particularly, the first reactor is operated at a temperature of from about 35 to about 60°C. For example, the second reactor or, more particularly, the first reactor may be operated at a temperature of from about 50 to about 60°C. Additionally or alternatively, the first reactor, or more particularly, the second reactor may be operated at a temperature of from about 35 to about 49°C.

In yet further embodiments of the invention, the first reactor may be operated with a hydraulic retention time of from about two hours to about five days. For example, the first reactor is operated with a hydraulic retention time of from about three days to about five days. In further embodiments, the solids/sludge retention time may be from about 2 days to about 5 days.

In certain embodiments of the invention, the second reactor may be operated with a hydraulic retention time of more than 10 days.

In still further embodiments, the second reactor is operated at a pH of from about 6.5 to about 7.9. For example, the second reactor may be operated at a pH of from about 6.8 to about 7.4, such as about 7.1.

In embodiments of the invention, the feed is an organic waste comprising biodegradable solids. For example, the organic waste may be a sludge, such as a waste sludge or a secondary sludge. Alternatively, the organic waste can be any other type of organic waste, such as oily sludge, industrial sludge, sewage sludge, food waste, oily waste, solid waste with a high organic content or any combination thereof.

In yet further embodiments of the invention, the first and second reactors further comprise pH, oxidation reduction potential (ORP) and temperature controllers. For example, in embodiments of the process, once the process is stable the ORP value may be maintained at a value that is less than -100 mV.

It is expected that the process outlined above will have application where there is interest in the treatment of wastewater with energy reduction and recovery, and where there are constraints on disposal of sludges. The process and the apparatus used therein can be used in both sewage and industrial wastewater treatment plants, and can be used in new plants or as a retrofit addition to existing facilities. In the retrofit scenario, the addition of the apparatus for running the disclosed process can also serve to expand the treatment capacity of the existing facility and hence avoiding the need for the reconstruction of existing treatment facilities as needs increase.

As such, in a second aspect of the invention, there is provided a waste treatment plant using the process of the first aspect and the embodiments disclosed herein. In an embodiment of the invention, the waste treatment plant may be a wastewater treatment plant, such as a sewage plant or an industrial wastewater plant.

In a third aspect of the invention, there is provided a reactor system for the treatment of organic waste, comprising: a first reactor and a second reactor that is downstream of the first reactor and is in fluid connection therewith, wherein the first and second reactors are adapted to use the process of the first aspect and the embodiments disclosed herein.

In an embodiment of the third aspect, the first reactor is primarily a hydrolysis/acidogenic reactor. In a still further embodiment of the invention, the second reactor is primarily a methanogenic reactor or is a single stage anaerobic reactor. In yet further embodiments of the invention, the first and second reactors further comprise pH, oxidation reduction potential (ORP) and temperature controllers.

Figures

The invention will now be described in further detail below, with the aid of the following figures.

- Fig. 1 Soluble chemical oxygen demand (SCOD) concentration in selected reactors of Example 1
- Fig. 2 Total VFA concentration in selected reactors of Example 1
- Fig. 3 Volatile suspended solids reduction in 2-stage system and single stage system in Example 1
- Fig. 4 Volatile solids reduction in single stage, 2-phase and 2 stage system in Example 1
- Fig. 5 Volatile suspended solids reduction in 2-stage & single stage system in Example 3
- Fig. 6 Methane production rate in 2-stage & single stage systems in Example 3
- Fig. 7 Volatile solids reduction in 2-stage & single stage system, pH in stage 2 reactor was maintained at 7.1 from 76th day of Experiment 5
- Fig. 8 Methane production rate in 2-stage and single stage systems in Example 5
- Fig. 9 Absolute quantification of bacteria and archaea by RT-PCR in mesophilic feed, the mesophilic single stage reactor, the mesophilic stage 1 reactor and the mesophilic stage 2 reactor of Example 3; and the thermophilic feed, the mesophilic single stage reactor, the thermophilic stage 1 reactor and the mesophilic stage 2 reactor of Example 5.

Description

As shown herein, the strict pH control used in a conventional 2-phase anaerobic system need not necessarily be the approach that is used to treat organic waste, such as sludge (e.g. oily sludge, oily wastewater, food waste, industrial sludge, sewage sludge and, particularly, sludge from wastewater treatment), in such systems. In contrast with the typical leading reactor in 2-phase systems, it is demonstrated herein that operating the leading reactor of a 2-phase system under alkaline conditions results in better solid reduction performance, more consistent production of CH_4 and improved VFAs production.

The proposed system has a hydrolysis/acidogenesis reactor which is different from the conventional acidogenesis reactor in a 2-phase anaerobic system. This is because the process used in the system does not aim to completely separate the VFAs production and consumption processes. Instead, it seeks to increase solid reduction and VFAs production *via in-situ* alkaline treatment, and so improves methane generation in the subsequent reactor. A relatively high pH (e.g. >6.5 , such as from about 6.5 to about 10.0, for example, from about 7.0 to about 9.0, or from about 7.5 to about 8.5, such as about 8.0) is applied in the first reactor that is higher than what has previously been used in 2-phase systems. This increased pH means that the effluent of the first stage reactor will not inhibit the activities of the second stage reactor(s). Therefore, in the system described below, the reactors have a 2-stage layout instead of a 2-phase layout. The first stage reactor is operated with largely similar operating parameters to those expected in an acidogenic reactor in a 2-phase layout, except for the higher pH, and hence use of alkalis to achieve this higher pH. The temperature of this first-stage reactor is controlled from about 35 to about 60°C, with the preferred temperature range being from about 50 to about 60°C. However, the first-stage reactor may be operated at a temperature of from 35 to 49°C. The pH and temperature ranges of the first-stage reactor promote both the chemical and biological destruction of suspended solids in the introduced sludge.

The 2-stage system requires minor or no pH adjustment after pretreating the biodegradeable solids (e.g. sludge). As such, there is less extra chemical cost involved. The comparatively lower pH values and temperatures applied are possible because the proposed process combines chemical action and biological enzymatic action to achieve hydrolysis and subsequent acidogenesis. These milder pretreatment conditions allow the discharge/effluent of the first stage to be fed to the second primarily methanogenic reactor with minor or no pH correction and no temperature correction. Without wishing to be bound by theory, these milder operating conditions in the first reactor also allow methanogens to survive therein and

help remove some of the metabolites produced (i.e. VFAs) which may have inhibited further production. Given this, and as demonstrated in the examples below, the methanogenic consortium in the first reactor is able to use the produced H_2 , CO_2 and VFAs to generate CH_4 .

The process for the treatment of organic waste comprising the steps of:
introducing a feed stream comprising organic waste into a first reactor;
generating an effluent from the first reactor; and
providing the effluent from the first reactor to a second reactor,
wherein the first reactor is maintained at a pH of from about 6.5 to about 10.0

It will be appreciated that the first reactor is provided upstream of the second reactor. That is, the second reactor is provided downstream of the first reactor, such that it accepts the effluent (i.e. the treated feed or sludge) exiting from the first reactor and uses it in its reaction processes.

When used herein, "downstream" means that a particular reactor is placed to receive at least some of the materials (e.g. the treated sludge or effluent) produced by a previous reactor, whether directly or indirectly (e.g. one or more further reactors may be placed between the downstream reactor and the originating reactor).

When used herein, "upstream" means that a particular reactor is placed to provide at least some of the materials (e.g. the treated sludge or effluent) it has produced to another reactor, whether directly or indirectly (e.g. one or more further reactors may be placed between the upstream reactor and the another reactor).

The feed used in the process may be an organic waste that comprises biodegradeable solids. For example, the biodegradeable solids may be particulates of organic matter and/or microbial cell walls. The organic waste may be a sludge (e.g. oily sludge, industrial sludge and sewage sludge) or other organic waste. For example, the feed may be a waste sludge from a wastewater treatment plant, a secondary sludge, food waste, oily waste or solid waste with a high organic content.

As mentioned above, the pH of the first reactor may be from about 6.5 to about 10.0. For example, the first reactor may be maintained at a pH of from about 7.0 to about 9.0 (e.g. from about 7.5 to about 8.5), such as at about 8.0. It will be appreciated that even if a specific pH is selected for maintenance, there will naturally be a fluctuation of the pH upon

the addition of more effluent and/or the addition of alkaline materials to increase or reduce the pH. Such fluctuations may lead to a temporary fluctuation in the pH value by up to one unit, such as half a unit, either up or down.

The pH values in the process can be monitored using a pH meter and a controller, such that when the pH value reduces below the desired level an amount of alkaline material is added to the first reactor to restore the pH value to the desired level. This monitoring and adjustment may be conducted automatically or by manual addition. It will be appreciated that the pH value is controlled by the addition of alkaline materials to the first reactor. These alkaline materials may be any alkaline material that will cause an increase the pH of the resultant mixture. Examples of alkaline materials include sodium hydroxide in the form of pellets or as an aqueous solution. Further examples include potassium hydroxide, calcium hydroxide and the like, again as a solid or as an aqueous solution (e.g. a 1N-5N aqueous solution).

The first reactor is primarily a hydrolysis/acidogenic reactor. As such, the first reactor is capable of hydrolysing organic particulates, such as microbial cell walls, through a combination of chemical and biological enzymatic action, while also being capable of maintaining a population of acidogenic bacteria to conduct acidogenesis in the reactor. This is achieved by using largely similar conditions to a conventional acidogenic reactor (e.g. the temperature is operated at from about 35 to about 60°C, such as from about 50 to about 60°C), but selecting of a pH range of from about 6.5 to about 9.0 (e.g. from about 7.0 to about 8.5, such as from about 7.5 to about 8.5 or from about 7.5 to about 8.25, such as about 8.0). This pH range is much higher than that used in conventional acidogenic reactors, which are operated with pH values well below 6.5 (e.g. 5.5). While the first reactor is primarily used to conduct the hydrolysis of particulates and to conduct acidogenesis, the pH environment within the reactor also enables a population of methanogenic bacteria to survive in the first reactor that is able to convert at least some of the hydrogen, CO₂ and VFAs produced by the acidogenic bacteria into methane. An advantage associated with having a population of methanogens in the first reactor is that it prevents the build-up of an inhibitory concentration of the acidogenic products (e.g. H₂) in the first reactor, thereby enabling production of said acidogenic products to continue at a greater efficiency.

It will be appreciated that the first reactor may be operated using any suitable hydraulic retention time. Suitable hydraulic retention times include from about two hours to about five days, such as from about three days to about five days. In addition, the first reaction may have a solids/sludge retention time of from about 2 days to about 5 days.

The second reactor is situated downstream from the first reactor and may be a methanogenic reactor or is a single stage anaerobic reactor. As the effluent, or treated sludge, from the first reactor has a higher pH, it may be fed directly into the second reactor with minor or no pH and no temperature correction, therefore reducing the costs and energy requirements associated with the overall process. It will be appreciated that more than one reactor may be presented downstream in series and/or in parallel from the first reactor.

When the second reactor is a methanogenic reactor (or reactors), the second reactor is primarily a methanogenic reactor. That is, the reactor may also contain, as a minor population, an acidogenic bacterial population capable of converting any unreacted acidogenic feedstocks from the first reactor into acidogenic products for use by the major population of methanogenic bacteria.

When the second reactor is a single stage anaerobic reactor, the second reactor may comprise both an acidogenic phase mainly comprising acidogenic bacteria and a methanogenic phase, mainly comprising methanogenic bacteria. In other words, when the second reactor is a single stage anaerobic reactor it may be a conventional single stage anaerobic placed downstream from the first reactor.

In the second reactors described above, the pH may or may not be controlled. In either case, the pH of the second reactor may be from about 6.5 to about 7.9, such as from about 6.8 to about 7.4, such as about 7.1. If the pH of the second reactor is controlled, the pH may be controlled to be from about 6.8 to about 7.4, such as about 7.1.

In use, the second reactor may have a hydraulic retention time of more than 10 days.

It will be appreciated that in order to ensure optimal control of the various processes, the first and second reactors may further comprise pH, oxidation reduction potential (ORP) and temperature controllers. Readings and adjustments to the reactors may be made manually or automatically by way of a processing device or means.

The first and second reactors may be continuous stirred-tank reactors, fitted with pH and temperature control devices and there may be a slight positive gas pressure inside said reactors. In general, the first reactor will be smaller than the second reactor, but it may also be the same size as the second reactor(s). Typically, when there is more than one second reactor, the first reactor will be the same size as the second reactors. The special

arrangement of reactors and the processing conditions described above enhances the hydrolysis and acidogenesis simultaneously, which allows the reactor system to achieve a combination of acid phase and staged behaviour.

By way of example, the process may be run and set up according to the following protocol.

- a. A modified acidogenesis dominant stage is inserted ahead of a typical single stage anaerobic reactor or methanogenesis reactor. Through a combination of start-up and operating conditions, the modified acidogenesis reactor allows culture and accumulation of a microbial consortium which has higher efficiency with respect to organic particulates reduction and VFAs generation at higher pH conditions.
- b. This two-stage anaerobic system is set-up with pH, ORP and temperature controllers. The pH of first-stage reactor is at 6.5-8.5 and temperature at 35 – 60°C. The first-stage of this continuous sludge digestion system can be operated with hydraulic retention time (HRT) of a few hours to 5 days.
- c. After a period of acclimation, the stage 1 reactor's microbial community can be expected to include about 99% Eubacteria and 1% Achaea. Aceticlastic methanogens including *Methanosaetaceae* and *Methanosarcinaceae* and hydrogenotrophic methanogens including *Methanobacteriales* and *Methanomicrobiales*, would be dominant in the first stage reactor.

It will be appreciated that the process described hereinbefore may be used in any waste treatment plant, where there is a need to deal with organic waste, such as a waste sludge from a wastewater treatment plant, a secondary sludge, oily sludge, industrial sludge, sewage sludge, food waste, oily waste or solid waste with a high organic content. For example, the process described herein may be used in a wastewater treatment plant for sludge treatment, such as a sewage plant or an industrial wastewater plant.

It will be appreciated that the process described herein will have particular application where there is interest in the treatment of wastewater with energy reduction and recovery, and where there are constraints on disposal of sludges. Energy recovery is of growing importance given the growing awareness of the energy-environment nexus. Current state-of-the-art wastewater treatment processes have a significant carbon footprint and the process disclosed above is a move towards energy neutral and, eventually, energy positive treatment

facilities. The process and apparatus used therein can be used in both sewage and industrial wastewater treatment plants, and can be used in new plants or as a retrofit addition to existing facilities. In the retrofit scenario, the addition of the apparatus for running the disclosed process can also serve to expand the treatment capacity of the existing facility and hence avoiding the need for the reconstruction of existing treatment facilities as needs increase.

Examples

Example 1

A 2-stage reactor was set up. The stage 1 reactor was operated under alkaline conditions and the pH was controlled at 8.0 by manual addition of from 1 to 5 N NaOH and the stage 2 reactor was operated at a pH of 6.8-7.4. The hydraulic retention time (HRT) of the two reactors was maintained at 5 and 10 days, respectively.

In order to compare the performance of the 2-stage system with a conventional 2-phase system and a conventional single stage system, a 2-phase and a single stage system were also established. The 2-phase system was operated at pH 5.5 ± 0.3 for phase 1 and at pH 6.8-7.4 for phase 2, and the HRTs of the phase 1 and the phase 2 reactors were 5 and 25 days, respectively. The single stage system was operated under a pH of 6.8-7.4 and a HRT of 15 days. All of the systems described above were operated at 35°C.

As the performance of sludge solubilisation, VFA production and consumption in a single stage reactor are simultaneous processes, the intermediate products of the processes, i.e. soluble chemical oxygen demand (SCOD) and VFAs, were at relatively low levels, as shown in Fig. 1 and 2. Given this, the comparison mainly focused on the performance of the 2-stage and 2-phase systems.

In the 2-stage system, a significant amount of SCOD was produced and accumulated in the stage 1 reactor. The highest SCOD concentration achieved was 12544 mg/L, with 27.28% of feed sludge solubilised. In contrast, in the 2-phase system, the highest SCOD achieved in phase 1 was only 6173 mg/L, which equalled to 14.14% of solubilised feed sludge.

The concentration of VFAs generated in the stage 1 reactor of the 2-stage system is displayed in Fig. 2, with acetic and propionic acids as the main compounds (60% and 20-

30%, respectively). The maximum total VFAs concentration produced in the phase 1 reactor of 2-phase system was less than half of the amount produced in the stage 1 reactor of the 2-stage system. From these results, it is clear that the hydrolysis and acidification processes were greatly enhanced by the *in-situ* alkaline treatment method.

It should be noted that methanogenesis in the stage 1 reactor of the 2-stage system was also active after an adaption period. The VFAs produced in the stage 1 reactor were consumed by existing methanogens to produce biogas. Hydrolysed sludge from the stage 1 reactor had a pH of 6.8-7.5, which can be directly fed to the stage 2 reactor without further pH adjustment. The stage 2 reactor was found to be capable of coping with a significant high loading of VFAs generated from the stage 1 reactor. This result suggests that the methanogens in the stage 2 reactor were able to quickly adapt to the loading shock and degrade most of SCOD and VFAs (Fig. 2).

Due to the enhanced hydrolysis and acidogenesis processes in the stage 1 reactor, the 2-stage system achieved higher volatile suspended solids (VSS) reduction compared to the 2-phase and single stage systems. The average VSS reduction efficiency of the 2-stage system was 43.8%, while that of the 2-phase and single stage system was 32.3 and 33.2%, respectively (Fig.3). The average volatile solids (VS) reduction efficiencies of the systems were 60.7% for the 2-stage system, 30.2% for the 2-phase system and 31.6% for the single stage system. From these results, it is clear that the 2-stage system had a significantly higher solids reduction capability than the 2-phase and single stage systems. Further, the biogas produced from the stage 1 reactor of the 2-stage system had a higher methane content compared to the other two systems (75.7% vs. 48.2% in phase 1 of the 2-phase system *versus* 65.1% in the single stage system).

After an acclimation period, the microbial community in the stage 1 reactor can be expected to include about 99% Eubacteria and 1% Achaea. Most of the cells were active. Aceticlastic methanogens including *Methanosaetaceae* and *Methanosarcinaceae* and hydrogenotrophic methanogens including *Methanobacteriales* and *Methanomicrobiales* were dominant in the stage 1 reactor, which, without wishing to be bound by theory, may explain the VFAs (mainly acetic acid) consumption and methane production in the stage 1 reactor.

Example 2

In order to check the capability of the 2-stage system at different HRTs, the system will also be tested using a HRT of 3 days on the stage 1 reactor of the 2-stage system. Results from this

experiment indicate that the stage 1 reactor also achieved more than 21% solubilisation of feed sludge with this shorter HRT.

Example 3

Stage 1 mesophilic & stage 2 mesophilic CSTR system

The 2-stage system was operated in a laboratory continuously stirred tank reactor (CSTR) system with 2.5 L/d sludge feed. The stage 1 reactor was operated at a pH of 8-8.5 (with the pH normally being around 8.0), with an HRT/SRT of 3 days and a temperature of 35°C. The stage 2 reactor was operated with an HRT/SRT of 17 days, a temperature of 35°C. The pH in the stage 2 reactor was not controlled. In a comparative single stage CSTR system, the reactor was operated at an HRT/SRT of 20 days, a temperature of 35°C and the pH was not controlled.

The results showed that the 2-stage system achieved significantly higher volatile solids (VS) reduction compared to single stage system (Fig. 4), and the average VS reduction efficiency was $57.60 \pm 3.68\%$, compared to $29.32 \pm 3.55\%$ achieved in the single stage system. In the single stage system, the pH was not controlled, but settled at a self-maintained level of between 6.8-6.95. The pH of the stage 2 reactor of the 2-stage system was also not controlled, and the pH value initially increased but then remained stable at 7.82.

Due to the increased VS reduction in the 2-stage system, methane production in the 2-stage system was higher than that achieved in the single stage system (Fig. 5). Compared to the single stage system, $31.54 \pm 6.46\%$ more methane (volume) was produced in 2-stage system over the time of the experiment.

Example 4

The 2 stage system described in Example 3 was also operated on a pilot scale with an 18 L/day feed in. Similar to Example 3, the stage 1 reactor was maintained with a pH range of 8.0-8.5 (normally 8.0), a temperature of 35°C and an HRT/SRT of 3 days. The stage 2 reactor was operated at an HRT/SRT of 17 days, a temperature of 35°C and the pH was maintained within a range of 6.8-7.2, with very little active control. The results showed that $69.09 \pm 5.21\%$ of VS reduction was achieved in pilot system.

Example 5

Stage 1 thermophilic and stage 2 mesophilic CSTR laboratory system

The above 2-stage system was operated in a laboratory CSTR system with 2.5L/d sludge feed. The stage 1 reactor was operated at pH 8-8.5 (normally was at pH 8.0), HRT/SRT of 3 days and 55°C, and stage 2 reactor was operated at an HRT/SRT of 17 days, at a temperature of 35°C. The pH in stage 2 reactor was not controlled during the first 75 days of the experiment, but was then controlled at pH 6.8-7.1 (normally was 7.1) from day 76 of the experiment. A single stage CSTR system was also set up for comparative purposes. In the single stage system, the reactor was operated at HRT/SRT of 20 days, at a temperature of 35°C and with no control of the pH.

The results demonstrated that significant VS reduction was achieved in the 2-stage system (Fig. 6). Without pH control in the stage 2 reactor, the average VS reduction in the 2-stage and single stage systems were $66.79 \pm 3.01\%$ and $30.04 \pm 3.65\%$, respectively. During the first 75 days of the experiment, the pH in the stage 2 reactor increased to about 7.85 and remained stable, without pH control. Over the same period, the pH in the single stage system maintained itself at 6.8-6.95.

From day 76 of the experiment, the pH of the stage 2 reactor was maintained at 7.1 and the VS reduction in the 2-stage system was further enhanced. The average VS reduction in the 2-stage and the single stage systems were $78.56 \pm 1.88\%$ and $33.39 \pm 4.17\%$, respectively from day 76 to the end of the experiment. During the whole experimental period, the average VS reduction in the 2-stage and the single stage systems were $72.65 \pm 6.53\%$ and $31.65 \pm 4.26\%$, respectively.

With respect to methane production, more methane (volume) was produced in the 2-stage system (Fig. 7). Compared to single stage system, $32.80 \pm 6.75\%$ more methane (volume) was produced in 2-stage system when the pH was not controlled in the stage 2 reactor during days 0-75 of the experiment, while $40.05 \pm 4.81\%$ more methane (volume) was produced in 2-stage system from day 76 onwards, when the pH was controlled at 7.10 in the stage 2 reactor. During the whole experimental period of 0-141 days, $36.73 \pm 6.78\%$ more methane (volume) was produced in the 2-stage system compared to the single stage system.

Example 6**Microbiology involved in single and 2-stage laboratory CSTR systems**

The sample from feed, single stage & mesophilic stage 1 and stage 2 reactors (Example 4) as well as the samples from thermophilic feed, single stage & thermophilic stage 1 and mesophilic stage 2 reactors (Example 5) were collected and analyzed by reverse transcription polymerase chain reaction (RT-PCR) to investigate the microbial community involved in both single & 2 stage systems. The dominance of bacteria and archaea in the samples are shown in Fig. 8. It was found that the methane species of *Methanomicrobiales*, *Methanobacteriales*, *Methanosaetaceae*, and *Methanosarcinaceae* were found in both feed and in each bioreactor, the controlled pH at 8.0 in mesophilic and thermophilic stage 1 reactors did not inhibit the cultivation of methanogens in stage 1 reactor.

CLAIMS

1. A process for the treatment of organic waste comprising the steps of:
introducing a feed stream comprising organic waste into a first reactor;
generating an effluent from the first reactor; and
providing the effluent from the first reactor to a second reactor,
wherein the first reactor is maintained at a pH of from about 6.5 to about 10.0.
2. The process of Claim 1, wherein the first reactor is maintained at a pH of from about 7.0 to about 9.0.
3. The process of Claim 2, wherein the first reactor is maintained at a pH of from about 7.5 to about 8.5.
4. The process of Claim 3, wherein the first reactor is maintained at a pH of about 8.0.
5. The process of any one of the preceding claims, wherein the first reactor is primarily a hydrolysis/acidogenic reactor.
6. The process of any one of the preceding claims, wherein the second reactor is primarily a methanogenic reactor or is a single stage anaerobic reactor.
7. The process of any one of the preceding claims, wherein the first reactor and/or second reactor is operated at a temperature of from about 35 to about 60°C.
8. The process of Claim 7, wherein the first reactor is operated at a temperature of from about 50 to about 60°C.
9. The process of Claim 7 or Claim 8, wherein the second reactor is operated at a temperature of from about 35 to about 49°C.
10. The process of any one of the preceding claims, wherein the first reactor is operated with a hydraulic retention time of from about two hours to about five days.
11. The process of Claim 10, wherein the first reactor is operated with a hydraulic retention time of from about three days to about five days.

12. The process of any one of the preceding claims, wherein the second reactor is operated at a pH of from about 6.5 to about 7.9.
13. The process of Claim 12, wherein the second reactor is operated at a pH of from about 6.8 to about 7.4.
14. The process of Claim 13, wherein the second reactor is operated at a pH of about 7.1.
15. The process of any one of the preceding claims, wherein the organic waste comprises biodegradable solids.
16. The process of Claim 15, wherein the organic waste is a sludge, food waste, oily waste, solid waste with a high organic content or any combination thereof.
17. The process of Claim 16, wherein the sludge is a waste sludge, a secondary sludge, an oily sludge, an industrial sludge or a sewage sludge, or any combination thereof.
18. The process of any one of the preceding claims, wherein the first and second reactors further comprise pH, oxidation reduction potential (ORP) and temperature controllers.
19. A waste treatment plant using the process of Claims 1 to 18.
20. The waste treatment plant of Claim 19, wherein the waste treatment plant is a wastewater treatment plant.
21. A reactor system for the treatment of biodegradable waste, comprising a first reactor and a second reactor that is downstream of the first reactor and is in fluid connection therewith, wherein the first and second reactors are adapted to use the process of Claims 1 to 18.
22. The reactor system of Claim 21, wherein the first reactor is primarily a hydrolysis/acidogenic reactor.
23. The reactor system of Claim 21 or Claim 22, wherein the second reactor is primarily a methanogenic reactor or is a single stage anaerobic reactor.

24. The reactor system of any one of Claims 21 to 23, wherein the first and second reactors further comprise pH, oxidation reduction potential (ORP) and temperature controllers.