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A View of Anaerobic Digestion: Microbiology, Advantages and Optimization

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Abstract: *Anaerobic digestion is an efficient technology widely used in biodegradable waste treatment, in which both pollution control and energy recovery could be achieved. Sewage sludge generated by waste water treatment plants is an ideal candidate for anaerobic digestion, for the total amount of sludge could be considerably reduced during the digestion process with a large sum of biogas produced as energy resource for heating, electricity or vehicle power. Although complex microbial community structures and interrelationships in anaerobic digestion process lead to the difficult of managing and maintaining the system, there has been various advanced methods developed to optimize the anaerobic digestion technology. Co-digestion of feedstocks from different sources and pre-treatments with chemical agents, physical methods or biological organics are all proved to be effective methods for enhancement of anaerobic digestion technology in the aspects of pathogen destruction and biogas production.*

Keywords: *anaerobic digestion, sewage sludge, co-digestion, pre-treatment.*

1. Introduction

Anaerobic digestion (AD) is the process of decomposition and stabilization of organic matters by microorganisms under an oxygen-free environment, leading to the formation of biogas containing methane and carbon dioxide [1]. It provides a good method for biodegradable waste material treatment, reducing pollution from household life, agriculture and industrial operations while in the same time producing energy to offset the fossil fuels used during the digestion process. As one of the most efficient technologies for waste treatment, AD based on a complex microbial structure and relationship exist in the reaction system, with different types of microorganisms dominating in different stages of the digestion process, jointly maintaining the stability of the reaction system. AD technology is now widely used by the Water Industry for the treatment of sewage sludge generated by urban wastewater treatment, for it manifests numerous significant advantages, such as a lower amount of final sludge volume with low energy requirement and a higher pathogen destruction ability along with a high biogas production [2]. Biogas produced from AD process mainly contains carbon dioxide and methane, and could be treated as environmentally sustainable energy resource to provide heat, electricity and vehicle power. Hence, the enhancement of biogas production has become a common target in municipal and industrial wastewater treatment plants (WWTPs) all over the world. As AD is such a popular technology for biodegradable solid waste and sewage sludge treatment, numerous advantaged enhancement technologies have been developed to optimize the AD process, especially for a more abundant biogas production. Co-digestion and pre-treatment are two commonly used ways for AD optimization. By mixing with different types of waste from diverse sources or pre-treated by acid, alkali, high temperature etc. the digestion rate and methane production could be increased considerably [3].

The essay aims to provide a general view of biodegradable waste AD treatment at four aspects as follows. Firstly, four stages of AD process are articulated to provide a general introduction of AD principle. Secondly, different species of microorganisms associated with AD along with their relationship and reactions during digestion process are comprehensively illustrated to give an account of the microbiology of AD. Thirdly, advantages and disadvantages are described in the context of sewage sludge AD treatment. Finally, enhancement methods for biogas production, pathogen destruction and co-digestion are critically examined for optimization of AD technology.

2. Basic principles of anaerobic digestion

The theory of anaerobic digestion has developed through several phases before coming into the point that the 'four-stage' theory is generally completed and widely accepted all throughout the world. These four stages of AD theory depict the basic principles and process of the AD of organic material, including hydrolysis, acidogenesis, acetogenesis and methanogenesis.

2.1 Hydrolysis

The first step of AD of organic matters is hydrolysis, which allows macromolecule organic matters to be broken down into small molecule substances to pass through cell membrane and be assimilated by methanogenic bacteria in the latter stage. The process of hydrolysis is operated under the action of microorganisms-secreted hydrolases, such as amylase, lipolytic enzyme and protease, with following material conversions: cellulose is translated into simple sugars, long-chain polypeptides are broken down into amino acids, while fats and lipids are degraded into fatty acids and glycerol, all of which can be utilized by cells and participate into following acid-forming and fermentation processes.

2.2 Acidogenesis

Acidogenesis is the second step of AD, decomposing the small organic molecules produced in the previous step, forming alcohols and volatile fatty acids (VFA) under the action of various acid-producing bacteria. In acidogenesis stage, the rate of acid production is high, and the pH of the system decrease rapidly with a moldy smell released. The output of terminal products depends on the ecological conditions, microbial community structures and the types of substrates in the AD system, with the main terminal products of CO_2, H_2, lactic acid, ethanol, formic acid, acetic acid, propionic acid, butyric acid, etc., participating into the third stage of AD.

2.3 Acetogenesis

Terminal products generated in acidogenesis stage are further conversed in acetogenesis process with the action of hydrogen-producing acetogens. CO_2 and various acids from last stage are transformed into H_2, HCO_3^-, CH_3COOH with a relatively small amount of CH_4, NH_3, H_2S, N_2, CO_2 and H_2SO_4 generated. The acetogenesis process involves the decomposition of a large amount of organic acids, so that the pH of the system rises sharply during the reaction.

2.4 Methanogenesis

The final stage of methanogenesis converted acetic acid into methane and carbon dioxide by two groups of methanogenic bacteria. The first group, aceticlastic methanogens, utilize acetate directly with the help of methyltransferase and splits it into CH_4 and CO_2. This group produces approximately 72% of methane in the stage. And the second group is hydrogenotriophic methanogens, which uses hydrogen as electron donor and carbon dioxide as electron acceptor to produce methane, taking up 28% of the total methane products [4].

The methanogenesis stage is an important step in the whole AD process with not only methane produced but also fatty acid split by methanogenic bacteria. The split acid plays a significant role in regulating the pH value in the system. In addition, the conversion of hydrogen into methane can effectively reduce the partial pressure of hydrogen and benefit the activities of acid-forming bacteria in the AD process.

3. Microbial species and interactions in anaerobic digestion systems

3.1 Microbial species associated with anaerobic digestion

There are diverse and complex species of microorganisms in the AD system, which can be generally divided into two groups: non-methanogenic and methanogenic bacteria.

Non-methanogenic also known as acidogenic bacteria including hydrolytic-fermentative bacteria, hydrogen-producing acetogens and homo-acetogens, generally exist in the first three stages of AD process. hydrolytic-fermentative bacteria mainly composed of cellulolytic bacteria, carbohydrate decomposing bacteria, proteolytic bacteria and lipolytic bacteria. Cellulolytic bacteria are often the control species of the speed-limiting step of AD due to the difficulties in the decomposition of cellulose. Most of the hydrolytic-fermentative bacteria are strictly anaerobic bacteria such as *Bacteriaceae* spp. and *Clostridia* spp. and with a small part of facultative anaerobes such as *Streptococci* spp. and *Enterobacteriaceae* spp. Hydrogen-producing acetogens and homo-acetogens exists in the third stage of AD process with typical floras of *Acetobacterium woodii* and *Clostridiun aceticu*, helping to consume hydrogen and to maintain a proper hydrogen partial pressure [5].

Methanogenic bacteria are obligate anaerobic bacteria existing in the last stage of AD process, with typical species of *Methanosaeta* spp. and *Methanosarcina* spp. These bacteria belong to prokaryotes, having a very simple cell structure without nucleus [6]. The cell wall of methanogenic bacteria contains substance of polysaccharide and polypeptide instead of peptidoglycan, whilst the lipid composition of the cell membrane presents a lack of glyceride. All methanogenic bacteria can only proliferate in environments with relatively low redox potential under -300mV. The presence of oxygen will suppress the growth of methanogenic bacteria and leads to an ecological imbalance in the AD system. Other parameters such as temperature and pH value in the AD system are also important. Methanogenic bacteria are very sensitive to surrounding environment and have an optimized living condition with 35℃ ~40℃ in neutral pH value. The productive period of methanogenic bacteria is long up to 4 ~ 6 days, leads to a long start-up period of AD equipment and a limit in the time of reaction process of anaerobic treatment.

3.2 Microbial interrelationship in anaerobic digestion system

3.2.1 Interrelationship between non-methanogenic bacteria

Different species of non-methanogenic bacteria appear in sequences in the AD process with hydrolytic-fermentative bacteria come first followed by hydrogen-producing acetogens and homo-acetogens respectively. The interspecific relationships between all kinds of non-methanogenic bacteria participate in AD process are mainly mutualism, showing a win-win process that the former bacteria provide nutritional substrate for the latter, while the latter species remove the inhibition for the former ones.

3.2.2 Interrelationship between methanogenic bacteria

The relationship between different species of methanogenic bacteria is mainly manifested in the competition for substrate. The proliferation of *Methanosaeta* spp., which has a low pace of growth, is benefited when the AD system has a low concentration of acetic acid, due to its higher capacity in ingesting substrate compared with *Methanosarcina* spp. On the contrary, *Methanosarcina* spp. grow rapidly when there is a high concentration of acetic acid in the system [6].

3.2.3 Interrelationship between non-methanogenic and methanogenic bacteria

Non-methanogenic and methanogenic bacteria share complex interactions in the AD process. They are closely related and cooperate to maintain the stability of AD system. The interrelationship between these two groups of microorganisms are mainly manifested in the following five aspects.

(1) Non-methanogenic bacteria provide necessary nutritional substrate to methanogenic bacteria. The complex organic compounds such as cellulose, protein and fatty acids are fermented by non-methanogenic bacteria into simple small compounds like hydrogen, carbon dioxide and acetic acid that can be directly utilized by methanogenic bacteria to produce methane. Life activities of non-methanogenic bacteria output the carbon source and nitrogen source needed for the growth and metabolism of methanogenic bacteria.

(2) Non-methanogenic bacteria produce a suitable redox potential for methanogenic bacteria. Entrance of oxygen into AD system during the filling process is inevitable and would greatly inhibits the growth of methanogenic bacteria. The presence of non-methanogenic bacteria especially the facultative bacteria can help to consume the oxygen and reduce the redox potential during AD process so that the proliferation of obligate anaerobic microorganism such as methanogenic bacteria in the system would not be obviously suppressed.

(3) Non-methanogenic bacteria remove toxic substances for methanogenic bacteria. Phenol, benzene, hydrogen and heavy metal ions such as Zn^{2+}, Cd^{2+}, Ni^{2+} etc [5]. in raw materials would have toxic effects to methanogenic bacteria. However, various species of non-methanogenic bacteria have

the abilities to degrade the benzene ring and cyanide with a generation of hydrogen sulfide, which can then react with heavy metal ions to form metal-sulphide precipitation and thereby relieve the toxic effect to methanogenic bacteria.

(4) Methanogenic bacteria scavenge metabolic waste and relieve feedback inhibition for non-methanogenic bacteria. Accumulation of hydrogen or acids produced by non-methanogenic bacteria during the hydrolysis, acidogenesis or acetogenesis steps in AD system would inhibit the production process associated with the same components. The higher the cumulated concentration of substrate, the stronger the inhibition will be. However, in the methanogenesis stage in AD system, the methanogenic bacteria consume the former metabolite step by step, so that the metabolic waste would not be accumulated too much to result in a serious feedback inhibition to non-methanogenic bacteria.

(5) Non-methanogenic and methanogenic bacteria co-maintain a suitable pH value for the AD system. The hydrolysis process operated by non-methanogenic bacteria produce a large sum of acids, which would significantly reduce the pH value of AD system. While methanogenic bacteria can utilize those generated organic acids to avoid the acid-accumulation to a certain extent, thus the pH value in the AD system would not exceed the pH threshold of the associated microorganic living environment.

4. Application of anaerobic digestion in sewage sludge treatment

4.1 Introduction of anaerobic digestion of sewage sludge

Sewage sludge refers to residual semi-solid material produced by activated sludge process in municipal and industrial WWTPs. It comprises a large sum of waste activated sludge and contains a certain concentration of heavy metals, organic micropollutants and pathogens, which have potential hazard to the environment and lead to stringent legislation for sewage sludge treatment all throughout the world. Anaerobic digestion (AD) is now a reliable and sustainable method favuored by water industry for sewage sludge treatment, as it has the ability to greatly reduce the finial amount of sludge solid and effectively destruct pathogens while transferring waste organic matters into biogas which can be used as energy resource. Besides, there are various other advantages in sewage sludge AD process such as reduction in energy consumption and improvement of dehydration performance, which will be detailed in the following, promoting AD method becoming more and more popular for sewage sludge management in urban wastewater treatment. There are various important parameters that can affect the AD process of sewage sludge treatment including pH, alkalinity, temperature, retention times, carbon-nitrogen ratio (C/N), trace elements etc. In order to find the most suitable reaction conditions for sewage sludge AD treatment under different actual situations, various types of AD process have been developed, including mesophilic and thermophilic digestion judging by the temperature, standard-rate digestion and high-rate digestion judging by the reaction rate, one-stage digestion and two-stage digestion judging by the series in the whole AD process etc. Although these processes have numerous advantages and are strictly selected and optimized during practice, presence of disadvantages and limitations such as low biogas production are there, calling for further enhancement of sewage sludge AD method.

4.2 Advantages of anaerobic digestion for sewage sludge treatment

The advantages of providing AD method in sewage sludge treatment are mainly manifested in the following five points.

(1) The energy consumption and investment cost are low during the digestion process. Compared with traditional aerobic digestion method, AD method requires no aeration to blast air into reactors, which enable it to eliminate blast aeration equipment and simplify its react tanks, thus a large sum of energy would be saved during the sewage sludge anaerobic disposal and the cost of equipment construction would be relatively reduced.

(2) Bio-energy such as biogas and biomass are produced in sewage sludge AD treatment. The fermentation of organic solid generates a great sum of methane, which has high calorific value and can be collected as energy resource for heating and power generation. It is proved that methane produced by sewage sludge AD treatment in WWTP in developed countries can meet approximately 33% - 100% of the electricity demand for treatment plants [7]. And for factories in developing countries, such as Qindao WWTP in China, the generated heat and electricity from methane and other biomass can help to cover 80% - 90% of the heating demand [8] and contribute greatly in capacity adjustment for Chinese

industries.

(3) Sewage sludge AD treatment produce a lower amount of final waste sludge solid compared with traditional disposal methods. Approximately 2/3 of the organic matters are absorbed by microorganisms in traditional aerobic treatment methods lead to a large accumulation of waste bio-solid volume. However, in the AD method, there is only a relatively small amount of organic matters assimilated into microbial cells, and most substrates are decomposed to form methane and carbon dioxide, so that the amount of final waste sludge production become lower with a more stable character to benefit the further disposal.

(4) AD method has a greater ability in degrading pathogen and various refractory organics in sewage sludge. The destruction of pathogen is mainly through dominant species in the system, whose growth and reproduction process release heat and intermediate substances that can inhibit the bioactivity and physiological toxicity of pathogen. For refractory organics, specific targeted microorganisms can be cultivated in the system to promote the utilization and degradation of these contaminants in waste activated sludge.

(5) Providing AD method for sewage sludge treatment can greatly limit the odor generation and effectively improve sanitary conditions in WWTPs, without excessive addition and discharge of nutrition elements such as nitrogen and phosphorus. This method reduces the exposure of living environment to pollutants and has broad prospects for development.

4.3 Disadvantages of anaerobic digestion for sewage sludge treatment

The advantages of sewage sludge AD technology mainly exist in the following aspects. On one aspect, AD treatment requires a longer start-up process, due to the long generation period and the low proliferation efficiency of anaerobic microorganisms participating in the digestion process. Only when the amount of sludge inoculated in the system increased to a certain concentration, can the start-up rate be relatively accelerated. On the other aspect, AD system requires complicated operational and management steps, and the balance of its digestion process is hard to be maintained, due to the difference in traits and characteristics between various bacteria species existing in the reaction system. An inappropriately excessive organic loading rate in the system would result in acid inhibition to methanogenic bacteria, so that the microbial balance in AD process would be destroyed and the whole system would eventually collapse. Nevertheless, there are other disadvantages for providing AD technology in sewage sludge treatment such as unfavourable hydrolysis kinetics, along with low methane production and biodegradability [9], all of which state the demand of optimization and enhancement for AD technology.

5. Optimization of anaerobic digestion

5.1 co-digestion for different types of waste

Co-digestion is a widely used enhancement method for AD treatment, mixing two or more than two types of biodegradable waste in one interactor in the digestion process. This method has been proved effective in adjusting reaction condition and improving energy conversion in AD systems. Carbon-to-nitrogen ratio (C/N) is one of the most important parameters affecting the effectiveness of AD treatment for biodegradable solid waste. When the value of C/N exceed the threshold, the amount of nitrogen would be insufficient and the buffer capacity of the system would be weaken with pH valve going down easily, inhibiting the digestion effect of solid waste in the reactors. The process of digestion would also be inhibited if C/N reaches an excessive low value, for the ammonium salt would be accumulated in the system to manifest a toxic effect on dominant bacteria. The generally utilized C/N radio for microorganisms is 25-30:1, however, it can be considerably changed during the AD process.

One of a particularly strong reason for co-digestion of feedstocks from different sources is to provide an appropriate C/N ratio, so that a better nutritional environment for dominant bacteria could be created in the system to enhance the digestion process. Co-digestion of a high C/N ratio feedstocks such as corn sticks and fallen leaves with a low C/N ratio feedstock such as mammal excrement can adjust the ratio closer to ideality. Researches proved that sewage sludge co-digestion with different types of feedstocks including kitchen waste, agricultural residues, animal excrement, landfill leachate, algae or vinasse can all enhance the efficiency of AD, either on BOD removal or on VS reduction along with other improvements in methane production, sludge dewatering performance etc. Saev et al. found that when sewage sludge mixed with cucumbers at a ratio of 9:1, the removal of COD during AD process increased 30.8%, from 42.9% leaping to 73.7% [10]. Nevertheless, addition of certain metals to the feed material has been found to optimize AD treatment. It has been demonstrated that supplementation of Ca, Fe, Ni, and Co in a thermophilic nonmixed reactor can help to efficiently remove propionate at high levels of volatile fatty acids. Co-digestion of potato waste with cattle manure could be improved in terms of methane production by adding 2.5 mg/L heave metal of Cd^{2+}, Fe^{2+} or Ni^{2+} [3].

Co-digestion method in AD optimization for different types of waste has been widely operated in WWTPs all over the world. Greversmithlen urban WWTP in German would be a good example, for 30% kitchen produced oil were mixed with sewage sludge, leading to a 4-times increase in sludge digestion and a 113% carbon neutrality rate, providing electricity for not only itself but also public power grid outside the plants [8]. As C/N ratio vary widely for different types of feedstocks, raw materials added into system for co-digestion should be strictly measured and detected to make sure the neutralization of each other could reach an ideal ratio.

5.2 biogas production

Biogas is an environmentally friendly fuel produced during the process of sewage sludge AD treatment. It contains approximately 55% - 60% methane, along with 33% - 40% carbon dioxide and a relatively small amount of hydrogen, hydrogen sulphide. moisture, siloxanes etc. Biogas has various utilization pathways such as heat and steam production, electricity generation, chemicals production and vehicle fuel supply, so that there is always a great need towards biogas production enrichment in the field of AD treatment. Pre-treatment and co-digestion are two reliable ways to achieve biogas enrichment.

5.2.1 Pre-treatment for biogas production

Feedstock pre-treatment can help to increase biogas production in AD process, especially for the treatment of material that contain high concentration of cellulose or lignin. Various pre-treatment methods have been developed to decompose recalcitrant polymers in AD system physically, chemically or thermally to increase the start-up speed and reaction rate during the digestion process, and thus the biogas production would be accordingly increased.

Acid pre-treatment is one of the most common pre-treatment method in AD process to enrich biogas. It inhibits the growth of hydrogen-consuming bacteria and promotes cell fusion to increase the amount of dissolved organics in sludge cells, which is an necessary characteristic for high biogas production. Liu et al. monitored the impact of hydrogen production in sewage sludge AD process with acid pre-treatment, and found that 100g sewage sludge pre-treated for 24 hours under condition of pH=3 and 24℃ had a maximum cumulative hydrogen production up to 14.66mL [11].

Alkali pre-treatment is another advantageous pre-treatment method in AD. The principle of alkali pre-treatment in promoting biogas production is similar to acid per-treatment, for both of what dissolve the cell wall of microorganisms in some degree and increase the assimilation amount of organic substrates. It was found that the degradation rate of paper waste could be increased when adding NaOH at 10% [12]. However, alkali pre-treatment should be controlled in an appropriate range of condition. Excessive concentration of alkali or overused pre-treated time would result in a generation of toxic compounds and reduce the biogas production rate.

Thermal/thermochemical pre-treatments are also effective ways to promote biogas production. Thermal hydrolysis of solid waste occurs in the reactor when the temperature increased to a certain degree in the AD system, resulting in acceleration of material decomposition and biogas generation. However, if the system is overheated, the biological activity of functional bacteria would be inhibited and the biogas production would decrease correspondently. Mottet et al. detected a sequencing AD process under 55℃ after thermal pre-treatments under different temperature (110℃, 165℃, 220℃ respectively), and found the optimal pre-treat temperature at 165℃. The COD and VS removal rate increased 15% and 18% respectively at the optimal temperature, and the biodegradation rate increased from 47% to 61% [13]. Nevertheless, when the chemical agents are provided together with thermal pre-treatment, the enhancement effect would be greater. Thermochemical pre-treatment under 100℃ with NaOH or H_2SO_4 for kitchen solid waste has been found to dramatically increase not only biodegradability but also methane yield [8].

Others pre-treatment methods such as ultrasound pre-treatment, microwave pre-treatment, biological pretreatment and joint pre-treatment are also developed as advanced technology for biogas enrichment. Although most of the methods are still in the experimental phase, it has been proved that oxidant such as O_3 or H_2O_2 joint with microwave or ultrasound pre-treatment could significantly promote digestion rate in AD process, and thus leaded to a satisfactory increment in methane production.

However, although pre-treatments for feedstocks greatly enhance biogas production ability in the AD treatment, the cost would be correspondently increased due to the utilization of relative chemical agents or heat energy provided in the pre-treatment process, and the economic benefits of WWTPs would be affected in a certain degree. It is highly suggested that effective measures should be done to find a balance between biogas production value and the investment cost.

5.2.2 Co-digestion for biogas enrichment

Synergistic mechanism between different types of biodegradable waste in AD system helps to increase the reaction rate and total amount of biogas production. Researches proved that sewage sludge treated by the method of continuous-flow mesophilic anaerobic digestion (MAD) produced 21% more methane when adding 20% kitchen waste (calculate in VS), and when mixed with grease waste at a ratio of 40:60 (calculate in VS), the methane yield increased 285% [14]. Nevertheless, when 5% infected slaughter wastewater are mixed with sewage sludge in AD system, the methane production is proved to be 4.7 times larger than that yield in a single-feedstock digestion process. Fungi can also be an effective additive to participate in the co-digestion when sewage sludge AD treatment are operated. The rate of methane production has been proved to increase 26% when sewage sludge and the *Chlorella* sp. were mixed at a volume ratio of 85:15 [15].

However, the additions of co-digestion feedstocks are often accompanied by extra produced biogas residue, which raise the volume of final solid generated and increase the cost for further disposal. Hence, co-digestion substrates are suggested to be less than 25% of the total solid disposed in AD reactors, so that the extra produced residue would not be overloaded to significantly affect the biogas production rate and the further disposal cost in biodegradable waste AD treatment.

5.3 Pathogen destruction

Destruction of pathogen in AD process is mainly through the growth and breeding of dominant microorganisms in the system. The heat and intermediate substrate produced by dominant bacteria during their metabolism can reduce the toxicity and physiological activity of pathogens. As pathogen destruction is such a complex procedure, parameters of temperature, pH, feedstocks properties, processing time and NH_4^+-H concentration can all be factors that affect sterilization process considerably.

In terms of temperature, it has been proved that thermophilic anaerobic digestion (TAD) method has a higher capacity in inactivating pathogen than mesophilic anaerobic digestion (MAD) method. While the temperature in MAD reactor raised from 30℃ to 35℃, time needed for pathogen destruction could be significantly shortened.

pH is considered another important factor for pathogen destruction in AD process, for it affect the concentration of volatile fatty acid (VFA), which is a vital intermediate product for microorganism survival. When pH decreased in AD system, ionic VFA would be gradually transferred to molecular VFA, which can diffuse into cell membrane and perform a toxic effect to pathogens. Nevertheless, the concentration of NH_4^+-H could also be affected by pH in the system. Controversial views have been demonstrated by Salsail that high pH condition promotes the forming of molecular NH_3, which can effectively destruct the cells of *Salmonella* spp., so that slightly increase the system pH might have positive effects for pathogen destruction [16]. However, an over-high pH condition could have a negative impact on the growth of methanogenic bacteria and results in a final collapse for the whole AD system. Hence, a lower pH in certain degree is more likely to be used as a reliable method for pathogen destruction.

Although there are rare literatures about advanced enhance method on pathogen destruction, it is widely accepted that high temperature and low pH in certain limit along with a longer processing time could be an effective combination for pathogen destruction during AD process.

6. Conclusion

Anaerobic digestion (AD) is an effective environmentally friendly technology widely used in biodegradable solid waste and sewage sludge treatment with numerous significant advantages. It can not only decompose waste organic materials from different sources and considerably reduce waste volume, but also generate biogas to provide heat and electricity as energy resources during the digestion process. There are various species of microorganisms with complex community structure and relationship exist in the digestion process, resulting in the difficulty of managing and maintaining AD system. Hence, parameters such as pH, temperature, C/N, concentration of NH_4^+-H, etc. should be adjusted strictly to avoid inhibition to dominant microorganisms in different stages of AD. Numerous advanced enhancement methods have been developed to meet the optimization of AD technology in terms of pathogen destruction and biogas production. Co-digestion is one of the most popular enhancement method, which provides an appropriate mixed C/N ratio for disposing different types of waste in the same time. Pre-treatment to feedstocks with chemical agents, physical methods or biological organics can also significantly improve the AD waste treatment efficiency.

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