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Research Progress on Methane Production from Anaerobic Fermentation of Food Waste

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Abstract. Anaerobic fermentation of food waste for methane production can help realize waste resource utilization and the "dual carbon" targets. We examine biochemical process and technology development of this method in full detail, covering how reaction happens at each stage and how equipment has changed over time. Also, we look at how key parameters affect methane production. It is worth noting that carbon-nitrogen ratio and temperature, together with external additives, can change efficiency in different ways. The results show that co-fermentation substrate adjustment and carbon-based material addition can avoid system acidification, and directional control of microbial community is expected to improve gas production stability. Current studies focus on single factor control and verification in laboratory scale, which makes it hard to apply in practice. Future work should examine multi-factor coupling mechanisms. Also, we should push results from lab to actual engineering applications. This review tries to build systematic knowledge framework for this field. In fact, results can be used as reference for large-scale application and process optimization of food waste anaerobic fermentation technology.

Keywords: Food waste, anaerobic fermentation, methane, technological progress.

1. Introduction

With the acceleration of urbanization in China and the rapid development of the catering industry, the generation of food waste continues to increase, placing tremendous pressure on the urban environment. According to data from the National Bureau of Statistics, the national food waste generation reached approximately 108 million tons in 2018 and has continued to rise [1]. As of 2024 alone, the amount of food waste separated from municipal solid waste in cities and counties was approximately 30 million tons [2]. If these organic wastes are treated using conventional landfill methods, not only will they occupy substantial land resources, but they will also lead to the direct release of large amounts of uncontrollable methane into the atmosphere, thereby exacerbating the greenhouse effect [3]. Against this background, the harmless treatment and resource utilization of food waste have become a critical issue in urban environmental management in China.

Anaerobic fermentation of food waste to produce methane can help solve these problems. The technology uses microorganisms to break down food waste under oxygen-free conditions, producing biogas where methane is the main component, so that the waste can be stabilized and made harmless while the resources are recovered. It is worth noting that the potential is large if all kinds of urban

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and rural food waste in whole country are converted to bio-natural gas using anaerobic fermentation, and the production can exceed 500 billion cubic meters [4]. National Energy Administration points out that developing bio-natural gas industry from food waste is important because it can promote green energy transformation and ensure stable energy supply [5]. Also, this is expected to support the "dual carbon" goals. We should develop this technology actively and it has become key task for China to achieve "zero-waste city" construction and carbon neutrality goals. In fact, it is important for building circular economy system and can ensure energy security, and it helps respond to climate change [6,7].

Many studies have been done by researchers to solve these problems. For C/N ratio adjustment, co-fermentation with activated sludge can be used. Xue Xudong et al. [8] found that when food waste and activated sludge are mixed at 4:6 ratio with 6% total solid, 55% inoculum, and 40°C temperature, the methane production can reach best value. Also, international studies show that co-fermentation has balanced C/N ratio and good buffer capacity, so it can improve gas production [9]. For temperature optimization, Liu et al. [10] reviewed the inhibition factors in thermophilic anaerobic digestion and pointed out that ammonia inhibition and volatile fatty acids accumulation can work together at high temperature. Also, too high organic loading rate can inhibit methanogenesis [11]. Recently, researchers start to pay attention to exogenous substances. Quan Cui et al. [6] found that surfactants and PLA plastic affect acid production when they enter the fermentation system and the influence is obvious. Guan Run et al. [12] found that foaming problem in high-solid fermentation is related to enrichment of Fastidiosipila. For process technology, researchers keep looking for new methods to improve fermentation efficiency. Jiang Xinyue [13] studied ethanol fermentation pretreatment combined with Fe/C to enhance food waste anaerobic digestion, and found this combined method can improve methane yield. Chen Siyu [14] used yeast pre-fermentation with conductive materials to promote methanogenesis, and the results show that adding conductive materials can strengthen interspecies electron transfer. Chen Jiankun [15] studied carbon-based materials for enhancing anaerobic digestion, finding that these materials can relieve inhibition from ammonia and volatile fatty acids, and they can serve as carriers for microbial attachment to enrich functional bacteria. Zheng Xiaowei et al. [16] discussed how inoculum ratio and initial organic loading affect the startup process. Wang Zhenxiong [17] found that co-fermentation of rice straw with food waste can optimize C/N ratio, and adding mineral materials can enhance system buffer capacity. It is worth noting that although these studies provide important basis for optimizing food waste anaerobic digestion technology, there are still some shortcomings. Most current studies focus on single factor regulation, and pay less attention to system response under multi-factor coupling. The interaction between exogenous substances and microbial community succession is still not clear. In fact, the long-term stability of new enhancement technologies and how they can directionally regulate microbial communities need more study. Also, most studies stay at laboratory scale and lack verification of long-term stable operation under real engineering conditions, which limits the technology from scaling up.

Based on the background above, current research still has some gaps and we examine the recent progress of anaerobic fermentation technology for food waste methane production.We sort out the biochemical process and technology evolution. Then we compare methane yield and energy recovery under different conditions, and analyze key factors like C/N ratio, temperature and external additives. The microbial community and its effect on process stability is also examined. In fact, we look at current limitations and give suggestions for future work. This studyBy collecting existing studies, we build knowledge framework for this technology. The system response under multi-factor

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coupling is revealed. These results can be used as reference for understanding the process control principles.

2. Biochemical processes of anaerobic fermentation and technological evolution

2.1. Biochemical processes of anaerobic fermentation

Anaerobic fermentation of kitchen waste is a complex metabolic process completed by many microbial groups. We can divide it into four continuous stages: hydrolysis stage, acidification stage, acetogenesis stage and methanogenesis stage. It is worth noting that strong metabolic coupling exists between these stages. If metabolic imbalance happens in hydrolysis stage, it can affect stable operation of whole system through accumulation or consumption of intermediate products.

Hydrolysis stage is the first step of anaerobic fermentation and it can be a rate-limiting stage in the whole process. In this stage, we can observe that fermentative bacteria secrete various extracellular enzymes. These include cellulase and protease, also lipase. It is worth noting that the complex organic matter in food waste can be degraded into small soluble molecules such as monosaccharides, amino acids, long-chain fatty acids and other products. Food waste has high content of easily hydrolyzable components. This can improve hydrolysis efficiency. But if the hydrolysis rate is too fast, intermediate products may accumulate faster than downstream microorganisms can use them and the metabolic load in acidification stage will increase.

In acidification stage, acidogenic bacteria can convert hydrolysis products to volatile fatty acids (VFAs), alcohols, hydrogen and carbon dioxide. Then the pH drops. In fact, food waste has high carbohydrate content and initial pH is usually about 5.1. Because the pH is quite low, the acidification process can become very active and we can expect that VFAs accumulate in reactor and the concentration will become high in a short time, and this accumulation should induce acid inhibition phenomenon [7].

In acetogenesis stage, hydrogen-producing acetogenic bacteria convert volatile fatty acids like propionic acid and butyric acid to acetic acid and hydrogen. Also, carbon dioxide is produced in this process. If these intermediates cannot be metabolized and removed in time, the accumulation can inhibit acidogenic bacteria activity and this will affect system performance. It is worth noting that propionic acid accumulation can be a precursor signal that the system may become unstable. It is because hydrogen-producing acetogenic bacteria are sensitive to temperature and pH changes.

Methanogenesis stage is the final part of the process. It can be seen as the key step where energy recovery happens, because this is where the methane is produced and collected for further use. Methanogens use acetate, hydrogen as well as CO2 to generate methane. These bacteria are sensitive to environmental conditions, and pH, temperature, ammoniaconcentration, metal ions and other factors can affect their activity. In stable mesophilic anaerobic system, acetate-utilizing methanogens such as Methanosaeta can dominate the community, and they are important for the system stability. When the system is stressed by ammonia or volatile fatty acids, Methanosarcina can become dominant. It is worth noting that this community succession can be used as a reference for judging the system health status, and it can help us understand the system operation.

2.2. Technological evolution

Kitchen waste has high moisture content and organic matter. It is easy to rot. This makes it can be used as a suitable substrate for anaerobic fermentation, but we should note that this also brings some difficulties to process operation because the high water content can affect the fermentation

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efficiency and the system needs careful control. Traditional treatment methods cannot handle these perishable organic wastes well. In fact, anaerobic fermentation has lower cost and secondary pollution is small, so it becomes a mainstream path for kitchen waste resource utilization [6].

From composition view, food waste includes carbohydrates (36.4% VS), proteins, lipids and other small fraction components, which means it has high VS content and COD value at the same time, and for this reason it can show good biomethane potential in anaerobic digestion [7]. But the C/N ratio is low. This makes it hard to control the process. Carbon element can provide energy and cell carbon skeleton for microorganisms, while nitrogen element is necessary material for synthesizing proteins and nucleic acids, so we should maintain suitable proportion between these two elements to ensure normal metabolism of methanogens. It is worth noting that if C/N is too low, ammonia nitrogen accumulation happens in system and this can inhibit microbial activity. But if C/N is too high, microbial growth is limited and organic matter conversion efficiency can decrease.

Regarding the influence mechanism, rapid hydrolysis and acidification of food waste can cause volatile fatty acids (VFAs) accumulation. Then system pH drops and methanogen activity is inhibited. This "acid inhibition" phenomenon is expected to be the main reason for instability of single-phase anaerobic fermentation [8]. In fact, food waste has carbohydrates as high as 36.4% VS, and initial pH is only 5.1, so the digester can suffer from rapid acidification [7].

Low C/N ratio can cause acidification risk. We note that researchers have examined many control methods. Co-fermentation with activated sludge is expected to optimize C/N ratio. The activated sludge contains high nitrogen content. When mixed with food waste, overall C/N ratio can increase and buffering capacity is improved, so pH drop caused by VFAs accumulation can be avoided. In fact, we find that in domestic studies, when food waste and activated sludge are mixed at 4:6 ratio, with TS mass fraction 6%, inoculum amount 55%, and temperature 40°C, optimal methane production effect can be obtained, and influence order of multiple factors is inoculum > TS > temperature > ratio [8]. Also, international research confirms this finding and shows similar trend. Co-fermentation has more balanced C/N ratio and stronger buffering capacity, so it is regarded as effective method to improve gas production performance [9].

Temperature can affect anaerobic fermentation efficiency of food waste. Also, this effect is related to ammonia nitrogen inhibition. Thermophilic anaerobic digestion (TAD, 50-55 ℃) can improve hydrolysis rate and organic matter removal, but system stability is easy to be disturbed by inhibition factors because temperature has regulation effect on ammonia nitrogen form and toxicity [10]. Under high temperature conditions, ammonia nitrogen inhibition and volatile fatty acids (VFAs) accumulation can produce synergistic effect. It is worth noting that when treating protein-rich food waste, total ammonia nitrogen exceeding 3-5 g N/L can have toxicity to microorganisms [10]. In fact, the mechanism is that high temperature environment promotes decomposition of nitrogen-containing organic matter so ammonia nitrogen release is accelerated. At the same time, temperature rise moves dissociation equilibrium toward free ammonia (NH_3), and free ammonia has more membrane permeability than ammonium ion (NH_4^+), which can inhibit enzyme activity of methanogens. When methanogenesis is blocked, VFAs cannot be metabolized and can accumulate, making system pH drop, and then more free ammonia can be generated, forming mutual promotion inhibition relationship.

It is worth noting that MAD (35-40℃) has better stability than thermophilic digestion. However, when facing high organic loading rates, efficiency can be limited. In fact, this makes it hard to get good results. We compare fermentation performance under different organic loads. It is found that when we increase load from 2.5 g VS/(L·d) to 5.5 g VS/(L·d), methane yield can be improved. But if load is too high, for example 6.5 g VS/(L·d), it can suppress methanogenesis process [11].

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Recently, exogenous substances effect on food waste anaerobic fermentation has become a new research focus. In fact, these substances are non-natural components entering fermentation system with food waste, and surfactants together with polylactic acid (PLA) plastics can be seen as two typical representatives. Surfactants mainly come from residues of cleaning products such as dishwashing liquid and laundry detergent.PLA plastics mix into food waste as lunch boxes and packaging bags as biodegradable materials become popular. Studies show these two substances can affect acid production after entering fermentation system [6]. Surfactants have amphiphilic structure and can change microbial cell membrane permeability, thus affecting substrate contact efficiency and also the generation pathway of volatile fatty acids. In anaerobic environment, PLA plastics hydrolyze into lactic acid monomers, and although they can serve as easily degradable substrate, high concentration accumulation can also induce system acidification and it can increase process instability [6].

At the same time, we find that foaming in high-solid fermentation system can be related to enrichment of specific microorganisms. In fact, Fastidiosipila genus can secrete extracellular polymers during metabolic process and these polymers contain hydrophobic proteins and humic substances which can reduce gas-liquid interfacial tension and then bubbles are formed and stay stable so the system has foaming problem at the end [12].

3. Recommendations for future research

3.1. Deepen research on system mechanisms under multi-factor coupling

The efficiency of kitchen waste anaerobic fermentation can be influenced by many factors. These include C/N ratio, temperature, organic loading rate, and also exogenous substances [7-11]. But in current studies only single factor is usually examined and not enough attention is paid to what happens when multiple factors change together in the fermentation process and the coupling mechanism is still unclear [8]. For example, under high temperature condition (50-55°C), ammonia nitrogen inhibition and volatile fatty acid accumulation can produce synergistic effect and the organic loading rate change can interact with temperature factor which makes the system behavior complex [10,11]. It is worth noting that future work can use experimental design with multiple factors and systems biology methods to look at how the fermentation system responds when temperature, C/N ratio, organic loading rate and exogenous substances act together, and then we try to build prediction models. The results can be used as a reference for process optimization.

3.2. Elucidate the interaction mechanisms between exogenous substances and microbial communities

Surfactants and polylactic acid plastics are exogenous substances, and when they enter fermentation system the acid production can be affected [6]. Also, foaming in high-solid fermentation system relates to Fastidiosipila genus enrichment [12]. However, the long-term effect on microbial community structure and its causal relationship with metabolic function can be unclear. It is worth noting that we suggest future research can combine metagenomics and metatranscriptomics to study the community succession and functional response under exogenous substances, and identify key functional bacteria and their metabolic pathways. These results can be used as a reference for risk assessment and control strategy.

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3.3. Optimize the long-term operational stability of novel enhancement technologies

Many new intensification technologies appeared in recent years. These methods can show good potential for improving methane yield when they are tested in laboratory scale under controlled conditions, and the results from batch experiments demonstrate that the methane production can be increased. However, most existing studies only focus on short-term batch experiments. In fact, the long-term stability is important and the economic performance also needs consideration and these aspects are not well studied under continuous operation condition. Also, the directional regulation mechanism of microbial communities should be examined. We suggest that future research should carry out long-term continuous operation experiments. The long-term stability and shock load resistance of different intensification technologies should be evaluated systematically, and we should also analyze the operation cost. Then we can combine microbial community analysis to reveal directional regulation mechanism. The results can be used as a reference for engineering application.

3.4. Promote the translational validation of laboratory research findings for engineering applications

Most current studies are still at laboratory scale. They lack validation of long-term stable operation under actual engineering conditions and this limits the practical value of current findings. Kitchen waste composition has temporal and spatial variability [7]. In fact, simulated kitchen waste used in laboratory studies cannot reflect the complexity of raw materials in actual engineering, which means results from lab may not work well in real plants and this gap should be noticed by researchers. We should conduct pilot-scale and above engineering validation studies based on laboratory optimization. Also, it is worth noting that we need to examine long-term operation characteristics and stability under actual working conditions. At the same time, we can evaluate economic performance. This can help establish effective connection mechanism between laboratory research and engineering application in practice.

3.5. Enhance targeted regulation of microbial communities and construction of synthetic consortia

Anaerobic fermentation is done by many microbial groups together and this is a complex metabolic process where we can observe that different stages have tight metabolic coupling relationships in the whole system. In stable mesophilic anaerobic system, acetoclastic methanogens such as Methanosaeta usually dominate the community. However, when the system suffers from stress caused by ammonia nitrogen or volatile fatty acids, we can observe that Methanosarcina with stronger substrate adaptation ability can become the dominant group in the reactor. This kind of community succession can be regarded as reference indicator. In fact, it helps us judge the health status of the anaerobic system when we monitor the microbial community changes. For future work, directed regulation strategies of microbial communities should be examined. It is worth noting that target functional groups can be enriched by regulating the key ecological niche factors in reactor environment. At the same time, we can explore the construction and application of synthetic communities and we can combine strains with complementary metabolic functions and this can help improve the system stability and methane production efficiency.

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4. Conclusions

In summary, anaerobic fermentation technology for food waste treatment includes four biochemical stages which are hydrolysis, acidification, acetogenesis and also methanogenesis, and through these stages organic matter in waste can be converted to biogas where methane is main component. It is worth noting that this process can reduce waste amount and make the residue stable. Also, we can obtain renewable energy from this system. In fact, this technology should be important path for China to build waste-free cities and it can help achieve dual carbon targets.

In future research, we should examine the system mechanism when multiple factors are coupled because understanding this complex interaction is the foundation for improving the whole process and achieving better performance in real applications where conditions are changing and hard to predict. It is worth noting that how exogenous substances interact with microbial communities should be revealed through experiments. Also, we can try to improve the long-term stability of new enhancement technologies so that the system can run without serious problems. Lab results need to be transferred to engineering applications and verified in real projects. Directional control of microbial communities should be strengthened and this can help improve methane yield. In fact, policy support and market mechanisms need to be built so that the technology can be accepted by market and these steps can help promote industrial application of food waste anaerobic fermentation for methane production and support its sustainable development.

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