Analysis of the Current Status and Prospects of Research on Residual Sludge as a Carbon Source

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Abstract: In recent years, with the improvement of people's living standard, the nitrogen and phosphorus content in domestic and industrial wastewater has increased significantly, resulting in a lower carbon to nitrogen ratio of wastewater, and at the same time, a large amount of residual sludge is generated in wastewater treatment plants which is difficult and costly to treat. The pretreatment of residual sludge as a carbon source for reuse in wastewater treatment systems to enhance the efficacy of wastewater denitrification and phosphorus removal can realize the resource utilization of residual sludge and solve the problem of low carbon to nitrogen ratio of biological denitrification and phosphorus removal at the same time, which meets the needs of water environment in China at this stage. This paper describes the current research status of residual sludge as a carbon source and the mechanism of sludge hydrolysis and acidification and analyzes the application prospects of this technology.

1 INTRODUCTION

China's domestic wastewater treatment plants have low influent COD concentrations, low C/N in the effluent, and a lack of carbon sources for the denitrification process. To achieve the effluent discharge standard, wastewater treatment plants usually solve the problem by adding carbon sources (such as methanol, acetic acid, glucose, etc.) (Li 2016), which greatly increases the operating cost of wastewater plants.

Sludge is a byproduct of wastewater treatment and is an easily decayed and odorous biosolids produced during the biochemical treatment of wastewater. The cost of sludge treatment and disposal is high, reaching 1000-2000 Yuan/t (in terms of dry sludge), accounting for 20%-50% of the operating costs of wastewater treatment plants (Yu, Zhang, Li 2013). The residual sludge contains a large amount of organic matter, which can be used as a carbon source for wastewater denitrification, but the complex structure of organic matter in sludge is difficult to be used directly by microorganisms, and some pretreatment measures are needed to enhance the release of biodegradable organic matter.

In recent years, researchers have greatly improved the dissolved chemical oxygen demand (SCOD) concentration in sludge by releasing the embedded carbon from the residual sludge into the solution by cracking. The cracked sludge is returned to the bioreactor, which can provide an endogenous carbon source for the biological treatment of wastewater and improve the removal rate of nitrogen from wastewater so that the wastewater can meet the standard discharge. In the process, partial reduction of residual sludge can also be achieved. There is a growing interest in related research.

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2 STATUS OF RESEARCH

In the activated sludge treatment process, the organic matter content in the residual sludge accounts for about 40% to 60% of the total sludge production (Moreno Caselles, Prats, Moral 2006). The organic matter in the residual sludge is degraded by anaerobic hydrolytic acidification to transform the large molecule organic matter in microbial cells into small-molecule organic matter suitable as a carbon source. Due to the demand for carbon source by denitrifying bacteria and phosphorus removal bacteria in the wastewater treatment process, the original carbon source in domestic wastewater is insufficient to meet the demand for a carbon source in wastewater treatment, which in turn leads to excessive discharge of nitrogen, phosphorus and other substances in the effluent of wastewater treatment process (Jin, Wang, Xing 2020). At the same time, with the input of additional carbon sources, the efficiency of nitrogen and phosphorus removal of traditional wastewater treatment process has been improved, but the production of residual sludge from biological treatment of wastewater has also increased significantly (Wei, Houten, Borger 2003). The residual sludge is mainly composed of sludge colloids, inorganic substances, dissolved pollutants, etc., which contains a large number of pathogenic microorganisms, heavy metal ions, and other toxic and harmful substances, so the residual sludge will cause secondary pollution to the environment if it is not properly treated (Xiang, Zhang, Zhuang 2004).

Therefore, the development of wastewater treatment process with residual sludge as a carbon source has important guiding significance and engineering application value for domestic wastewater treatment technology as well as water environmental safety issues in China, which is in line with the needs of China's sustainable development strategy.

2.1 Mechanism of Residual Sludge Hydrolysis and Acidification

Anaerobic digestion of sludge is now generally accepted as a three-stage theory: hydrolysis stage, acidification stage, and methanation stage (Lu, Lai, Zhang 2009). The specific process is shown in Figure 1. The first stage is the hydrolysis stage, in which complex organic substances such as proteins, polysaccharide carbohydrates, and fatty acids are degraded into small molecules such as amino acids, monosaccharides, and fatty acids by anaerobic hydrolysis and related anaerobic bacteria; the second stage is the acidification stage, in which the hydrolysis products of the first stage are further degraded into small molecules such as hydrogen and acetic acid by the action of hydrogen and acetic acid-producing bacteria. The third stage is the methanation stage, i.e., the products of the second stage are further degraded by methanogenic bacteria to produce methane and other gases.

The first stage of hydrolysis is the rate-limiting stage in the three-stage theory because of the difficult degradability of sludge cell walls and macromolecular substances such as EPS (Extracellular Polymeric Substance). Among them, the hydrolysis acidification process is a degradation process in which organic substances are used as electron acceptors and donors, and fermenting bacteria convert the small-molecule organic substances produced by hydrolysis into simpler end products such as amino acids and fatty acids. Similarly, the methanation stage uses small molecules such as fatty acids from the acidification stage as a substrate for degradation, so the three stages of anaerobic digestion are interrelated and affect each other. Therefore, when the utilization rate of substrate is lower than the substrate yield, the yield of intermediate products will be accumulated, which will hinder the completion of the three stages of anaerobic digestion. In summary, the accumulation of degradable small molecules such as volatile acids can be promoted by increasing the rate of microbial cell lysis in the hydrolysis stage and inhibiting the methanation stage.

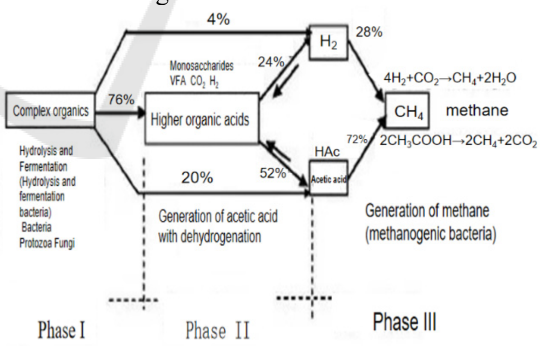

Figure 1: Three stage theory of hydrolysis acidification.

2.2 Technical Method to Promote Residual Sludge Hydrolysis and Acidification

Many scholars tend to resource sludge through anaerobic fermentation for acid production. However, acidic hydrolysis is the rate-limiting step in the process of anaerobic fermentation of sludge, so it needs to be pretreated first, and there are three main types of methods: physical, chemical, and biological.

2.2.1 Physical Method

The physical method is to break the sludge by external energy to increase its solubility, which is more conducive to anaerobic fermentation and acid production, including ultrasonic method, grinding method, hot water solution method, freezing and melting method, etc. The ultrasonic method uses the mechanical shear force of water to destroy the cell walls of microorganisms in sludge in a local high-temperature and high-pressure environment so that their contents flow out for subsequent treatment (Guo, Ma, Liu 2019). The increase in dissolved chemical oxygen demand (SCOD) after low-intensity ultrasound treatment of sludge indicates an increase in the leaching of organic matter from the sludge, which facilitates the subsequent treatment of the sludge (Liu 2011). However, the application of ultrasound technology has the problem of high energy consumption, and it is usually used in combination with other methods to reduce costs and increase the efficiency of sludge cracking. The heating method also destroys the floc structure of sludge, and treating sludge in the range of 120-160 °C increases the sludge solubility, leading to an increase in the content of dissolved proteins and carbohydrates, a significant increase in the rate of anaerobic digestion, and an increase in methane production (Xue, Liu, Chen 2015).

2.2.2 Chemical Method

The chemical method involves the addition of various chemical reagents, mainly oxidants (ozone, Fenton reagent, ClO2, etc.) and bases [NaOH, Ca(OH)2, etc.], to the sludge. The oxidizing agent can destroy the floc structure of sludge, dissolve the cell wall (membrane) of microorganisms, make the cell contents leach out, increase the concentration of SCOD in sludge, and improve the utilization rate of microorganism. The alkali treatment dissolves the fibrous components and organic flocs in the sludge, destroys the cell structure of microorganisms, releases the dissolved organic matter from the cells, and increases the content of biodegradable organic carbon in the sludge (Xu, Zhuan, Zhang, Chang 2018).

2.2.3 Biological Method

The biological method is mainly used to change the solubility of sludge by microorganisms or some enzymes, which facilitates the anaerobic fermentation process. The microbial method mainly degrades the organic components of sludge through the microbial flora contained in the sludge itself or by adding microorganisms, and is divided into 2 types: aerobic and anaerobic, usually anaerobic digestion has a better treatment effect and is more widely used. After anaerobic digestion of sludge first at high temperature and then at medium temperature, the sludge solubility increases, and methane production rises because all microorganisms contained in itself can find suitable conditions for growth (Ge, Jensen, Batstone 2010). Further, the direct addition of digestive enzymes, such as protease and α-amylase, can increase the production of VFAs and achieve sludge reduction (Luo, Yang, Yu 2011).

3 PROSPECT ANALYSIS

With the rapid development of industry and the increasing urban population, the discharge of urban sewage has increased, and in this context, the development of sewage treatment plants is on the rise. At present, the number of urban sewage treatment plants in China has exceeded 2000. During the operation of the wastewater treatment process, part of the sludge produced by the process is returned as reactants for biological reactions, while the remaining sludge is to be discharged outside the system. The amount of this remaining sludge is alarming, with its high-water content, large volume, easy decay, foul odor, and containing a large number of heavy metals, germs, and other toxic and harmful substances.

According to the "China Sludge Treatment and Disposal Deep Research and Investment Strategic Planning Analysis Report", with the popularity of sewage treatment facilities, sewage treatment efficiency, and the deepening of the degree of sewage treatment, urban sewage treatment plant sludge production has increased sharply. As China's urban sewage treatment plant sludge treatment and disposal capacity is insufficient, means backward, many of sludge has not been standardized treated and disposal, directly bring "secondary pollution" to the water, soil, and atmosphere, not only reduces the effective treatment capacity of sewage treatment facilities but also poses a serious threat to the ecological environment, while also causing a great waste of resources. A great waste of resources.

In contrast, China's research on wastewater treatment started very late; in the early 1990s, China's sludge treatment technology was at a preliminary stage, and a few wastewater plants were able to treat sludge simply through mechanical dewatering, thus reducing the water content of sludge from the original 97%-99% to 75%-80%, but there were still problems with the storage and reprocessing of treated sludge. In the last 20 years, sludge treatment technology in China has made great progress, but the research is not deep enough, no unified evaluation criteria have been formed, and there is a lack of reference in the selection of technical solutions.

To accelerate the speed of sludge treatment, during the 13th Five-Year Plan, the central government will invest 200 billion yuan for sludge treatment in sewage plants, and with the continuous breakthrough of sludge disposal technology and the promotion of policies, the sludge treatment, and disposal industry will soon usher in a blue ocean market. With the policy guidance, China's sludge treatment industry market demand has been released. It is predicted that the sludge treatment market size will reach about 86.7 billion yuan in 2023 according to the effective sewage treatment rate to the project.

Therefore, the realization of sewage resource utilization and effective development of internal carbon sources to achieve recycling not only make effective use of sludge but also reduce the generation of residual sludge, while achieving sludge reduction and resource utilization, killing two birds with one stone. Biological methods have a greater prospect of development because of their low environmental pollution, low cost, and effective sludge resource utilization. However, single biological methods often have limitations such as low removal efficiency and long duration of action, while synergistic action with fast-acting chemical or physical methods will improve the efficiency of anaerobic fermentation while reducing environmental pollution (Liu, Liu, Liu 2021). The residual sludge can be used as a high-quality carbon source to promote the efficacy of nitrogen and phosphorus removal from wastewater by cracking and then hydrolytic acidification. Future research should still focus on how to apply the laboratory technology for large-scale application, explore a more energy-efficient cracking method as well as a suitable dosing ratio, and study a solution suitable for the actual situation in China.

At present, nearly half of the sludge produced by the national sewage treatment plants has not been harmlessly treated, and the progress of investment in sludge treatment facilities is slow, and the development of the sludge harmless and resourceful disposal market still needs a process, through the active guidance of relevant national policies, the sludge harmless disposal industry will usher in a larger development opportunity.

4 CONCLUSIONS

The residual sludge cracking can be used as an endogenous carbon source for nitrogen removal in wastewater plants, which can simultaneously achieve residual sludge reduction and reduce the added carbon source, thus increasing the total nitrogen removal rate, improving the effluent quality, and reducing the treatment cost. A variety of physical, chemical, and biological methods are available to achieve effective residual sludge cracking, and the combined process is more effective. However, the following problems exist: first, how to achieve selective cracking, so that the proportion of carbon source is higher than that of N and P. Second, how to reduce the cost and achieve economy, since the release of SCOD from the sludge after cracking is accompanied by the release of N and P from the sludge. The research on the above issues may be a hot topic in the future.

For the study of using cracked sludge as a denitrification carbon source, it is necessary to further investigate the mechanism of sludge cracking, to determine which organic compounds are released from the floc after sludge cracking, and to explain their role in biological denitrification and phosphorus removal. In the process of sludge cracking, the reaction conditions need to be strictly controlled so that C, N, and P are released in a proportional manner, and the released C is much larger than N and P, in order to avoid additional nitrogen load to the system, which makes it difficult to remove organic nitrogen from the system, and also to avoid weakening the phosphorus removal effect for nitrogen removal.

In addition, when selecting the carbon source, the endogenous carbon source and the external carbon source can be complementary to each other, in order to save the treatment cost and improve the nitrogen removal effect as much as possible, so as to achieve a dynamic balance between the cost and the treatment effect.

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